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SUMMARY TECHNICAL REPORT OF DIVISION 6, NDRC

VOLUME 22

# ACOUSTIC TORPEDOES

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT  
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE  
JAMES B. CONANT, CHAIRMAN

DIVISION 6  
JOHN T. TATE, CHIEF

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WASHINGTON, D. C., 1946

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## NOTES ON THE ORGANIZATION OF NDRC

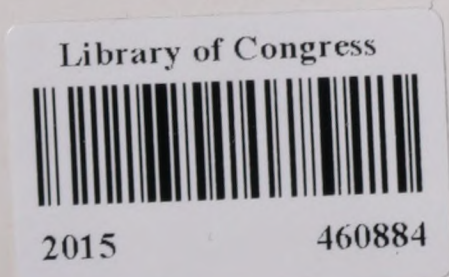
The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

- Division A — Armor and Ordnance
- Division B — Bombs, Fuels, Gases, & Chemical Problems
- Division C — Communication and Transportation
- Division D — Detection, Controls, and Instruments
- Division E — Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

- Division 1 — Ballistic Research
- Division 2 — Effects of Impact and Explosion
- Division 3 — Rocket Ordnance
- Division 4 — Ordnance Accessories
- Division 5 — New Missiles
- Division 6 — Sub-Surface Warfare
- Division 7 — Fire Control
- Division 8 — Explosives
- Division 9 — Chemistry
- Division 10 — Absorbents and Aerosols
- Division 11 — Chemical Engineering
- Division 12 — Transportation
- Division 13 — Electrical Communication
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- Division 16 — Optics and Camouflage
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## NDRC FOREWORD

AS EVENTS of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not dupli-

cated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Any great cooperative endeavor must stand or fall with the will and integrity of the men engaged in it. This fact held true for NDRC from its inception, and for Division 6 under the leadership of Dr. John T. Tate. To Dr. Tate and the men who worked with him — some as members of Division 6, some as representatives of the Division's contractors — belongs the sincere gratitude of the Nation for a difficult and often dangerous job well done. Their efforts contributed significantly to the outcome of our naval operations during the war and richly deserved the warm response they received from the Navy. In addition, their contributions to the knowledge of the ocean and to the art of oceanographic research will assuredly speed peacetime investigations in this field and bring rich benefits to all mankind.

The Summary Technical Report of Division 6, prepared under the direction of the Division Chief and authorized by him for publication, not only presents the methods and results of widely varied research and development programs but is essentially a record of the unstinted loyal cooperation of able men linked in a common effort to contribute to the defense of their Nation. To them all we extend our deep appreciation.

VANNEVAR BUSH, Director  
*Office of Scientific Research and Development*

J. B. CONANT, Chairman  
*National Defense Research Committee*

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## FOREWORD

A VERY substantial portion of the research and development effort of Division 6 related to acoustic homing control of torpedoes and mines. This effort led to the design and production of homing devices which found important Service use. The British, likewise, undertook research and development in this same field, but the results of their work apparently found limited Service application. Also, the enemy was not idle, for somewhat to our distress the Germans developed an acoustic homing torpedo; but, it should be added, reasonably effective counter-measures quite promptly became available — a fact, which, incidentally, is very pertinent to future consideration of devices of this type.

When about a year ago the plans were laid for the Division 6 summary report series, there was proposed for this volume material relating to actual structures. However, because of pressure of their other duties, it has not been possible for the persons competent to summarize the mass of material involved to undertake this task. All of this material has, however, been made available to interested Service technical personnel. Also, since the Division 6 report series was

planned, the Office of Research and Inventions asked for a comprehensive study and report on torpedoes. As a part of this project there was furnished to that office a report on guided torpedoes, and presumably this also is available to interested Service personnel.

This report will therefore be somewhat restricted in its scope. It includes, however, as Part I a general analysis of the problem presented, *Principles and Applications of Acoustic Homing Control to Torpedoes*, prepared by Dr. W. V. Houston, and as Part II a report *Echo-Ranging Torpedo Control Systems*, by Dr. V. M. Albers. This second report is peculiarly pertinent as it covers the less highly developed method of acoustic control and one which may hold considerable future promise.

In the bibliography appears a list of the more pertinent reports prepared by Division 6.

JOHN T. TATE  
Chief, Division 6

E. H. COLPITTS  
Chief, Section 6.1







## PREFACE

### Part I

THIS REPORT was prepared by the Columbia University Special Studies Group as part of the studies made in connection with Projects NO-94, NO-149, NO-157, and NO-181. It covers the sum of the theoretical studies associated with the application of acoustic control to torpedoes of various kinds.

Although some of the theoretical work was done directly by the Special Studies Group, much of this report is a compilation of experimental results and theoretical developments carried on by the various other groups concerned. Some attempt has been made to give credit to these groups for their work, but this has not been possible in all cases.

A major part of the report is concerned with torpedo self noise and its influence on control systems. Torpedo self noise appears to be the dominating factor that limits the use of such control systems so that methods for its control must constitute the principal objective of future research along these lines.

This report contains reference to specific developments only in so far as they are useful in illustrating the theoretical principles. Detailed descriptions of the various systems that were tried and of their success will be found elsewhere.

W. V. HOUSTON

### Part II

This report is intended to cover, as far as possible, the work which has been done in the development of echo-ranging control for torpedoes. It is assumed that the reader is familiar with conventional electronic circuits. The emphasis, in discussing the various systems, is on their functional behavior and on the details of circuit design which are unconventional.

It is important for the reader to bear in mind the fact that all of the systems described, except the General Electric system, are actually still in the research stage and the General Electric system is, at the time of preparation of this report, just in the pre-production stage. The chapters covering the various British systems are necessarily very brief since relatively little material is available about them.

The report is divided into four main parts. The first, which is essentially introductory, covers a review of terminology in underwater sound, the nature of the problem of echo-ranging torpedo control and a general description of the major components involved in all echo-ranging control systems. The second and third cover, respectively, the systems

developed for antisubmarine and anti-surface-ship service with a separate chapter devoted to each system. The fourth division contains an attempt at evaluation of the work which has been done up to the time of preparation of this report.

In discussing each of the systems a general description is first given with a block diagram in order to indicate the general principles utilized in the device. This is followed, in all cases where the information is available, by a detailed discussion of the major components of the system with individual circuit diagrams of each functional component.

This report is confined chiefly to the descriptions of the electronic gear which is used in the echo-ranging torpedoes since the application has so far been almost entirely to existing torpedoes which have been adequately described elsewhere. Only those physical characteristics which determine the behavior of a torpedo under echo-ranging control are noted.

VERNON M. ALBERS







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***PART I***  
***INTRODUCTION***

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## Chapter 1

### OBJECTIVES OF HOMING CONTROL

THE MODERN naval torpedo is a highly effective weapon by means of which a large explosive charge is detonated near the underwater part of the hull of an enemy ship. It is distinguished from a mine by the fact that it is self-propelled and can be directed toward a selected target.

Traditionally the torpedo is a weapon of stealth. It can be launched several miles from the target and travels underwater along its predetermined course. In many cases the explosion gives the first indication of immediate danger, and it is often difficult to determine whether the ship has been struck by a torpedo or has itself struck a mine.

However, the surprise feature of a torpedo attack is sacrificed when torpedoes are launched from airplanes. In such cases it is usually possible for the target ship to detect the launching of the torpedo and to take suitable evasive action. Even in the case of a submarine-launched torpedo, the wake produced by the ordinary steam-driven weapon and the noise made by the driving mechanism provide means by which the approach of a torpedo may be detected in time to take evasive action. This evasive action usually takes the form of turning directly toward or away from the oncoming torpedo. Such a maneuver presents to the torpedo, or salvo of torpedoes, such a narrow target that the probability of a hit is very much reduced. Furthermore, since the speed at which a torpedo travels may not be much greater than that of the ship, almost any turn may upset the nice calculations on which the aiming of the torpedo was based.

A simple torpedo is expected to follow a preset course at a specified depth, and the accuracy with which it does so is a measure of the effectiveness of the control mechanism. However, in order to determine what course to set, it is necessary for the torpedo officer to know the speed, course, bearing, and range of the target ship. The speed and the course are often difficult to determine, especially on the basis of the restricted view available through the periscope of a submarine, so that it is not surprising that many torpedoes miss their targets, even when no evasive action is taken. This fact is so well recognized that it is customary to fire salvos of as many as four torpedoes on slightly different courses in order to cover

the possible error in aim. This method has, of course, the additional advantage of being somewhat of a countermeasure to evasive action.

The object of a homing device is to make possible a lethal hit by guiding the torpedo to the target in spite of the evasive action that may be taken and in spite of errors in the original set course of the torpedo.

A homing device is intended to minimize the effect both of aiming errors and of evasive action taken by the target. Such a device makes use of some characteristic property of the target, so that when the torpedo comes within the homing range it no longer follows the preset course but is directed toward the target. In such a case the torpedo will eventually strike the target and explode, unless the speed of the target permits it to run away. No evasive action of the nature of changes in course is effective, since presumably a torpedo can maneuver as well as any ship against which it would be directed.

A homing device can be associated with various types of search procedure. One extreme is illustrated by the ExF42 mine and the ExFF3 torpedo. In these cases the torpedo is launched from the air or from a submarine and follows a circular path at the set depth until it picks up the target on which it then homes. The only information necessary for launching is that required to place the torpedo within its operating range of the target. This is quite feasible in the case of a torpedo launched from an airplane against a submarine that has been sighted on the surface, and possibly in some cases for a torpedo launched from a submarine against an attacking surface vessel.

In most cases, however, the effective homing range will be much smaller than the running range, and a preset course must be used to direct the torpedo into the neighborhood of the target. In this latter case the torpedo is aimed in the usual way and the homing mechanism serves to correct the course, if necessary, near the end of the run. In this form, the effect of the homing device may be described as an enlargement of the target. If the homing range is 100 yd, the effective target may be roughly pictured as extending 100 yd in all directions from the point of the target ship on which the device homes. This is, of course, only a crude way of looking at the matter. The effectiveness of each homing mechanism must be



worked out on the basis of its own particular properties.

The effectiveness of a homing torpedo depends principally on two features.

1. The effective homing range should be as great as possible and should not be confined to the direction straight ahead. Homing range straight ahead is of limited value, for the torpedo will strike what is straight ahead of it without any homing mechanism. On the other hand, too much homing sensitivity to the side may make the torpedo susceptible to certain types of decoy. Generally it seems desirable to have a long homing range rather uniformly distributed ahead of the torpedo.

2. The turning radius of the torpedo must be sufficiently short. It is quite important that the turning radius be shorter than the homing range if it is to get around so it can approach the target at all. On the other hand too short a turning radius makes for instability along the course and leads to difficulties in the automatic steering. The torpedo must be maneuverable enough so that it can keep pointed at the target, but it must also be steady on the desired course.

The advantages of homing devices are fairly obvious but it must not be forgotten that there are also disadvantages. Among them may be mentioned the following six.

1. The homing mechanism occupies space and weight that must be taken from either the explosive charge or from the fuel supply. The advisability of doing this requires a careful consideration of all the facts, with particular emphasis on the properties of the targets against which the weapon is likely to be used.

2. The homing mechanism introduces increased complication in manufacture and maintenance. The techniques involved in the homing devices may be quite different from those normally associated with torpedoes, so that a completely new type of training

may be necessary for adequate maintenance and operation. In large-scale planning this may be a very significant factor.

3. To gain an adequate homing range it may be necessary to operate at a lower torpedo speed than would otherwise be possible. In the case of acoustic homing it is the self noise of the torpedo that usually sets the limit to the homing range, and this noise increases rapidly as the torpedo speed increases. It must then be decided whether the necessary decrease in speed is justified by the advantages of the homing property. This decision involves a knowledge of the speed of the expected target ships, since obviously it would be useless to use a torpedo too slow to reach the target attacked.

4. Different homing systems sometimes tend to cause the torpedo to strike different parts of the ship. An acoustic torpedo that operates by listening tends to end its course in a stern chase and to strike near the propellers. An echo-ranging torpedo may, under some circumstances, tend to strike near the bow. These points of impact may not always be satisfactory since, although a hit on the propellers may be disabling, it may not be correct to assume that the ship will usually sink.

5. Most homing devices are subject to some form of more or less effective countermeasure which, if used, may make the torpedo less likely to hit the target than if the homing device had not been present.

6. Homing devices may limit the number of torpedoes which can be fired simultaneously without mutual interference. This is particularly true of acoustic listening torpedoes that may have a considerable homing range on each other.

In spite of these limitations it appears that the homing devices now known are definitely an advantage to the group using them since, in general, the number of torpedoes that must be launched to make a hit is markedly reduced.



## Chapter 2

### PROPERTIES OF ACOUSTIC HOMING SYSTEMS

VARIOUS TYPES of homing control have been suggested. Radio control would be convenient because of the extensive development of radio techniques. However, no radio waves of usable frequency are known that will penetrate water more than a very short distance. For this reason such a torpedo would have to be equipped with an antenna projecting out of the water. Such an appendage would seriously hamper the motion and steering of the torpedo and does not seem to be very practicable. On the other hand, torpedoes have been built with such antennas so they can be radio-controlled from a launching plane. However, they have not been extensively used.

Magnetic control has been suggested and may be practicable, but the intensity of the magnetic disturbance due to a target ship falls off so rapidly with distance that it seems very doubtful if homing ranges as great as 100 yd could be obtained. However, if countermeasures against acoustic homing devices appear to be highly effective, the development of magnetic homing may be justified.

It has also been suggested that some method of following up the wake of a ship could be used to produce a homing control. It is possible that such a device would operate satisfactorily, but its tactical usefulness would be somewhat limited. It would have to be fired so as to come in contact with the wake at some point not too far behind the ship, and it could not be used against a stationary ship. Furthermore in the case of a maneuvering target, the wake might be such a complicated affair that it would be difficult to follow. Nevertheless such a homing device may have its uses, although it has apparently not been developed sufficiently so that the results of extensive field tests are available.

The most promising type of homing control, and the one that has been the object of extensive study and development during the past four years is acoustic. Sound travels in water without too much attenuation as long as the frequency is below some 60,000 c. Although the ocean is not a homogeneous medium, and the sound traveling in it may be reflected, refracted, and scattered, sound signals can be sent for appreciable distances. For about thirty years sonic methods have been used for locating submarines, for communicating between submarines, and for communicating between submarines and surface ships.

In this connection much has been learned about the propagation of sound in sea water, and during the last few years this study, and the study of acoustic homing devices, has been carried to such an extent that it is possible to lay down in a general way the possibilities and the limitations of acoustic homing devices for subsurface use. This is not to say that no more research is needed, but the lines along which research needs to be done can be pretty well laid down.

Methods for sonic location of a target can be divided into two classes and homing devices based on each have been built.

1. Echo ranging. This is a method of determining the direction and distance of a reflecting body by the echo it sends back in response to a sound signal. The homing device must then respond to the echo in such a way as to direct the torpedo toward it.

2. Listening. In this method the sound travels in one direction only. To operate a listening method of homing control the target must produce noise. This noise is then picked up by the homing device which determines the direction from which the signal is coming and directs itself toward the target.

Both of the above methods have been tried for homing torpedoes and have been shown to work satisfactorily within certain limits. The listening method is the simpler, not only in its acoustic and electronic gear, but in the application to the torpedo controls of the information received. On the other hand it requires that the target ship make some noise in the adopted frequency range, and hence it is ineffective against a ship at rest and quiet. In connection with torpedoes for use against submarines, it appears that a submarine at considerable depth makes practically no noise, since the cavitation of its propellers is suppressed and it may be very quiet in the frequency ranges normally used. In addition, a listening device may be countered by the operation of a strong source of noise at a distance from the target ship. Such a decoy can be built to simulate a ship's noise very closely.

The echo ranging type of homing control is effective against a stationary target as well as a moving target, and would be effective against a deeply submerged submarine. To counter it appears to require some method of producing false echoes such as an



echo repeater. It is, however, more complicated in construction and the exact extent to which it is effective has not yet been determined in operational use.

The operation of either type of acoustic homing torpedo is limited by the conditions of the water. For the ranges normally under consideration, 100 to 1,000 yd, this is only serious under the worst conditions. Nevertheless it appears that such regions as Chesapeake Bay in the summer are so bad that echo-ranging operation over as much as 500 yd is improbable. Although both types of homing control are limited by refraction of sound in the water, the echo-ranging type is, in addition, seriously handicapped by reverberation and false echoes. Echoes from the bottom are so serious that satisfactory operation in shallow water is unlikely, and even reflections from the surface may occasionally be troublesome.

The operating range of any acoustic torpedo is most seriously limited by the torpedo self noise. This noise may be generated in the water because of cavitation of the propellers, cavitation on various parts of the body, and other causes, or it may be the noise made by the torpedo machinery. The noise due to cavitation can be reduced or eliminated by running the torpedo at a sufficiently great depth of submergence. If the torpedo is to be used as an antisubmarine weapon this is no additional complication, but if it is to be used against surface ships, the necessity of arranging for the torpedo to rise in the proper way to strike the target introduces numerous problems.

In any case the torpedo self noise increases with its speed, and it is probably safe to assert that the acoustic operating range of a high-speed torpedo can never be made so great as that of a slower torpedo. Nevertheless it may still be great enough to be useful. A high-speed torpedo is needed only in case the target is a high-speed vessel. The high speed of the target causes it to produce more noise than a lower-speed vessel and so to some extent counteracts the increased self noise of the torpedo. This advantage does not accrue in the case of an echo-ranging control where the range is not increased by an increase in target noise.

The study of torpedo self noise and of means for

reducing it constitutes the principal line of effort in the improvement of acoustic homing torpedoes. Two lines of attack are possible. One is the reduction of the noise at its source. This involves a study of propeller design and the general overall shape with the object of eliminating cavitation and reducing other types of water noise. It also involves the reduction of internal machinery noise due to gears, flow of high pressure air, and motion of high-speed parts.

The other line of attack is the attempt to reduce the hydrophone response to the noise that exists. This involves the selection of hydrophones whose directivity pattern is such that there is very little response to cavitation and other noise produced in the water. It also involves mounting the hydrophone in such a way that vibrations are not picked up from the body of the torpedo itself. In addition it may be helpful to modify the torpedo structure at various points in order to reduce the transmission of sound to the shell and through it to the hydrophones.

Much work has already been done along these lines but much more remains to be done before the best practical acoustic homing torpedo can be built.

A consideration of the importance of torpedo speed in reaching the target, and of self noise in reducing the homing range suggests that the ideal torpedo would have at least two, and possibly three, speeds. The maximum speed would be used for attacking the fastest ships. The self noise of the torpedo would be fairly high but the high noise of the target ship would override this in a listening torpedo, and in an echo-ranging torpedo some reduction in range would have to be accepted since the torpedo must have enough speed to catch the target.

Against lower-speed targets a lower torpedo speed could be used. The speed-changing mechanism would also increase the acoustic sensitivity to make use of the reduced self noise and so keep the effective acoustic range from being seriously reduced by the reduction in target noise.

It seems possible that careful selection of the various speeds and the best utilization of them might lead to the specification of an almost universal torpedo for use from submarines and possibly another for use from airplanes.

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## Chapter 3

# GENERAL OBSERVATIONS ON TORPEDO SELF NOISE

TO OPERATE properly, an acoustic torpedo must distinguish between the signal on which it is expected to steer and other noises that may be present. These other noises may be in the surrounding water or they may be in the torpedo itself. Careful measurements, made by the Bell Telephone Laboratories [BTL]<sup>5</sup> in rather deep water, indicate that far away from the shore the water background noise is principally due to surface disturbances such as whitecaps. It was found that when no whitecaps were present, the noise level at 25 kc was as low as -74 dbs,<sup>a</sup> while with many whitecaps it was as high as -50 dbs. Heavy swells seemed to have no effect in producing noise.

Water noises provide a limit below which no acoustic torpedo can be expected to operate. However, if the water noise is isotropic, i.e., if it comes equally from all directions, a directional hydrophone will respond to it very much less than to a plane wave coming along the direction of maximum sensitivity. The difference in response to these two types of sound is just the directivity index of the hydrophone. Because directional hydrophones are normally used, as well as because a torpedo is normally a rather noisy machine, the water noise is usually well below the torpedo noise and can be neglected.

### 3.1 IMPORTANCE OF SELF NOISE

This noise of the torpedo itself, as it affects the hydrophones in the torpedo, is normally the most important limiting factor in the operation of an acoustic torpedo. This is quite clear in the case of a torpedo that listens to the noise of the target ship. A torpedo has most of the characteristics of a ship, especially a submarine, on a small scale; and it is not likely that any significant difference in quality will exist between the noise of the target and the noise of the torpedo. Hence the discrimination must be made on the basis of intensity alone. When this is done, it is a fair general statement to say that acoustic control can be expected only when the root mean square

<sup>a</sup> The abbreviation "dbs" signifies decibels spectrum level and refers to the intensity of the noise in a frequency band 1 c wide. The reference intensity is that corresponding to a root mean square pressure of 1 dyne per sq cm. For a discussion of terminology and reference levels in sound measurements see Division 6, Volume 10, *Calibration Methods*, Chapter 4, "Types of Acoustic Measurements."

[rms] value of the target noise is equal to or greater than the rms response of the hydrophone to the torpedo self noise.<sup>b</sup> Sometimes it is possible, by special arrangements, to recognize a slightly lower signal, but frequently it is considered that operation is reliable only when the signal is somewhat above the self noise. Nevertheless, the above statement is a satisfactory rough criterion for estimating the acoustic operating range of any listening control.

A possible exception to the general statement may be the case in which the target noise is strongly modulated with the period of the propeller blade frequency. Since the top of a large ship propeller is nearer the surface of the water than the bottom, each blade may have its maximum cavitation as it passes through the top position. Since such propellers usually have a much smaller rate of rotation, the modulation frequency is lower and the target noise may be identified at a slightly lower level than indicated.

With an echo-ranging control the problem appears at first to be a little different. It may be possible to impose on the emitted signal such a character that it can be detected in the presence of noise. However, the advantage to be gained by this method is distinctly limited because the target is rarely a plane reflecting surface. In general it is made up of a number of surfaces and the result of their joint action tends to destroy the character of the incident ping and make it more like noise.

Hence for both types of acoustic control, it may be stated as a general approximate rule that for successful operation *the rms response of the hydrophones to the torpedo self noise must be less than, or at most equal to, the rms response to the signal from the target.*

Since in a listening torpedo the signal strength is fixed by the nature of the target and in an echo-ranging type it is not practical to increase the signal strength indefinitely, attention must be given to reducing the response of the hydrophones to the torpedo self noise. The condition is worded this way because it can be accomplished by (1) reducing the level of the noise generated and (2) reducing the sensitivity of the hydrophones to the predominant sources of noise. In order to apply either of these

<sup>b</sup> There is a possibility that characteristic modulations of noise may be present which could be used to give added discrimination.



methods, it is important both to identify the sources of noise and to study the means by which the noise is transmitted to the hydrophones.

### 3.2 EXTERNAL MEASUREMENTS OF TORPEDO NOISE

The simplest way of getting a preliminary estimate of torpedo noise is to measure it with a hydrophone fixed in the water, as the torpedo runs past. Possibly the principal difficulty in such a measurement lies in determining with sufficient accuracy the distance between the hydrophone and the torpedo that corresponds to the measured noise levels. Nevertheless measurements made in this way serve as a starting point for the general study of the problem, and in fact observations of different observers show a remarkable amount of agreement.

Figure 1 shows a series of curves based on the measurements of a number of different observers.<sup>1</sup>

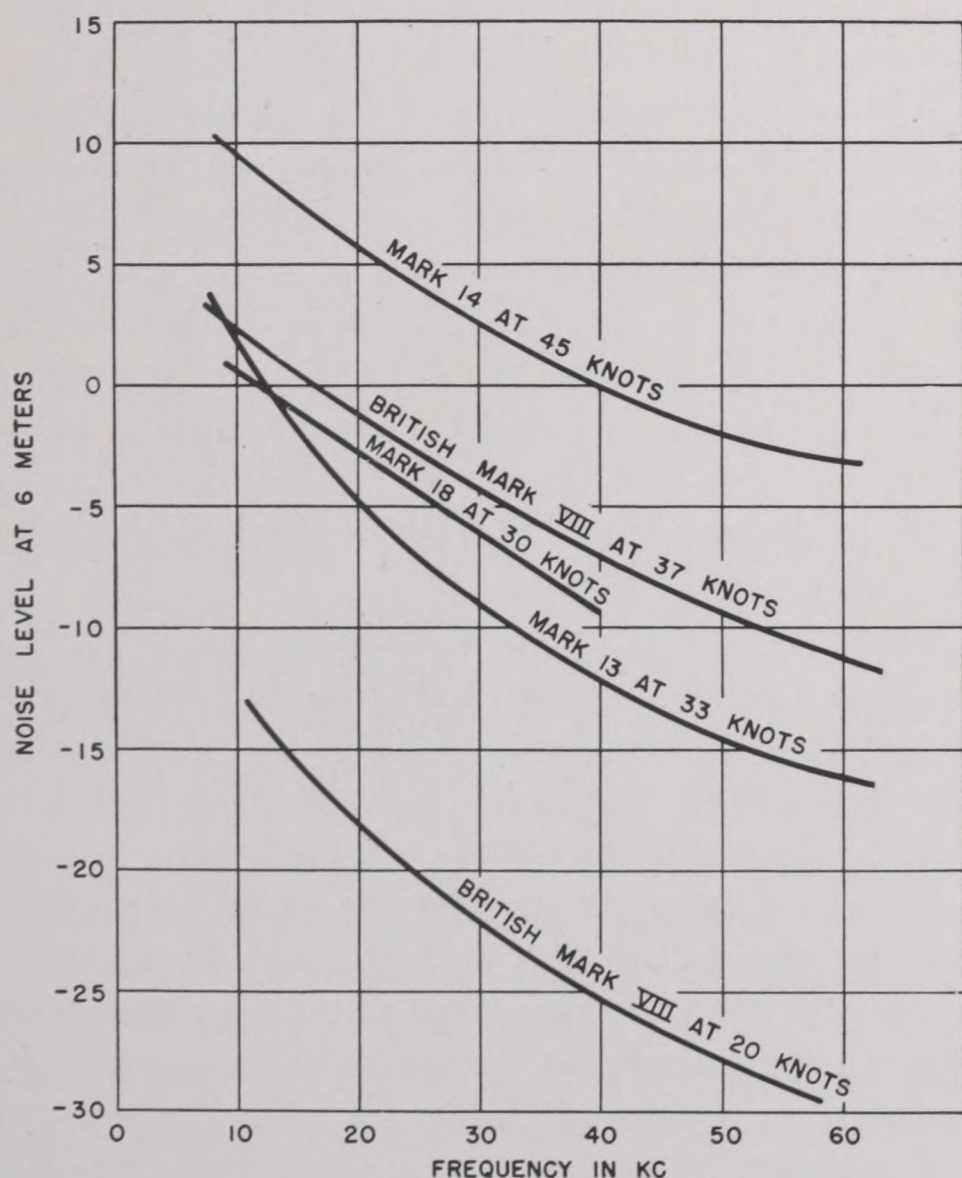


FIGURE 1. Noise level measurements on various torpedoes at a distance of 6 meters. These curves represent averages of a number of observers.

Although the observers differ somewhat among themselves, and in all probability the conditions of measurements were not identical, there is sufficient agreement among them to permit drawing the rough

average curves shown in the figure. From these curves a number of conclusions can be drawn.

1. Individual differences between different kinds of torpedoes seem relatively insignificant. In particular the Mark 18 electric torpedo is no quieter than the Mark 13 turbine-driven torpedo.

2. It is possible to plot a curve of torpedo noise as a function of speed at a given depth. This is done in Figure 2 which shows the noise level, at 25 kc, as a function of speed for torpedoes running 12 to 15 ft

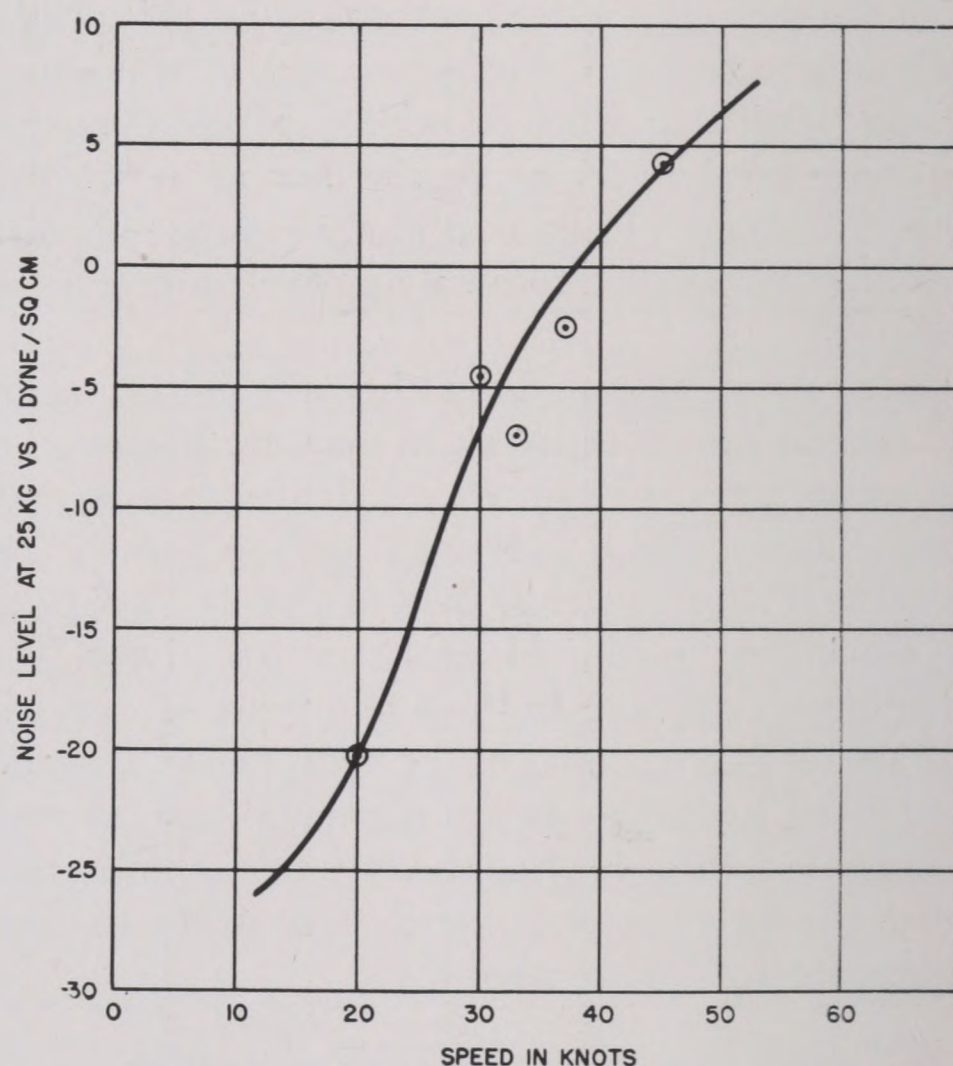


FIGURE 2. A curve of noise level at 25 kc as a function of speed, for an "ideal" torpedo. The points indicated were taken from the curves in Figure 1.

deep. A smooth curve drawn through these points may then be regarded as the noise-speed curve of an idealized torpedo, and it seems possible to discuss the properties of this ideal torpedo. This lumping of all torpedoes together must be viewed with some caution. The observations used refer to British, American, and one German torpedo only, and it may be incorrect to extend the generalization to other foreign torpedoes. It is possible that the British and American trends of development have been such as to lead to torpedoes that are very similar in their noise characteristics above 10 kc. Figure 3 shows the curve of Figure 2 with a large number of individual observations indicated. This shows that the dispersion of the measurements on any one type of torpedo is at least as great as any possible differences between different torpedoes. It is clear that the curve drawn



is not the one that would be drawn through the points if they were all given equal weight. However, if the observations for the same type of torpedo are first put together as for Figure 2 the fit is fairly good.

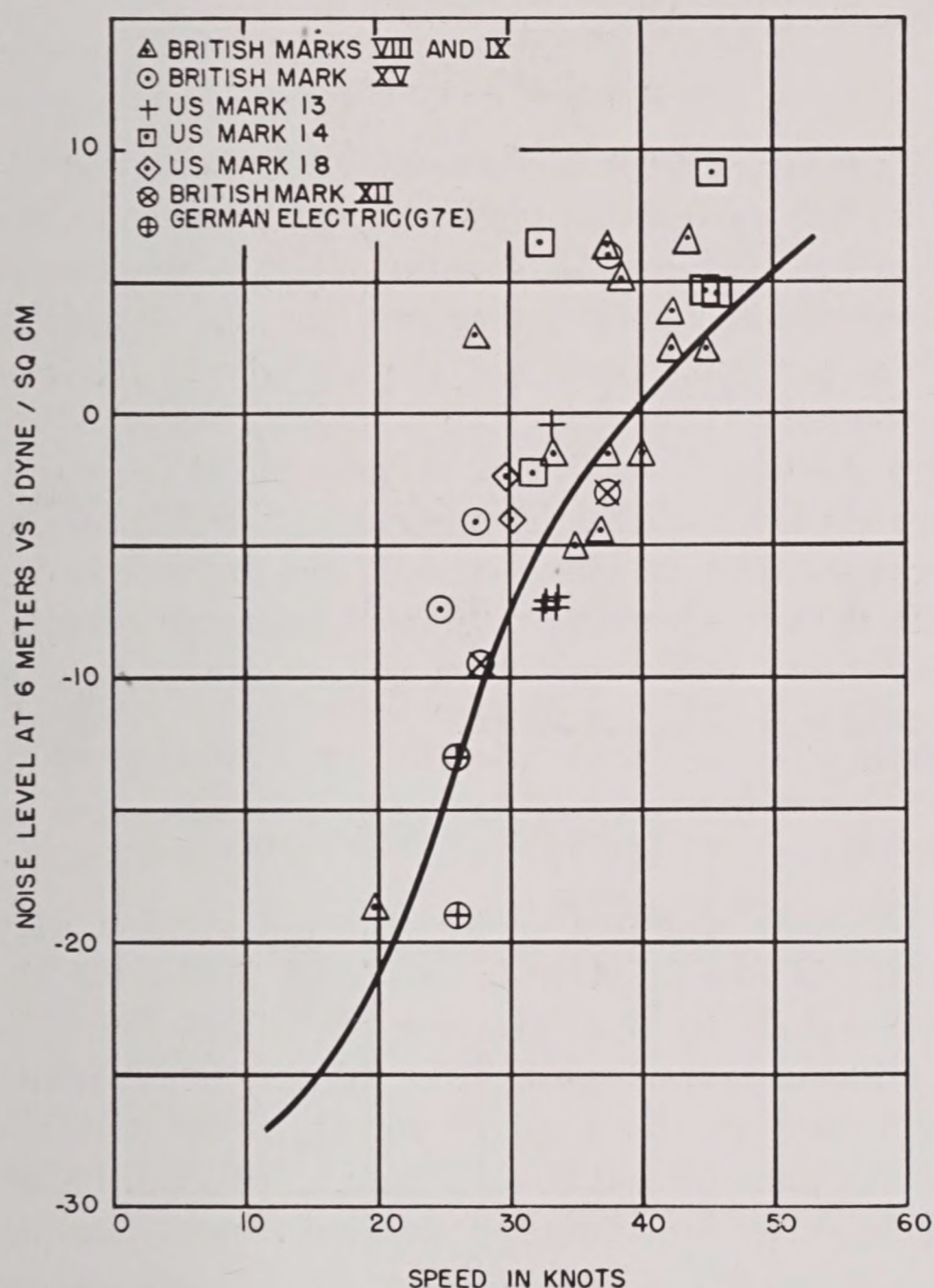


FIGURE 3. This curve is the same as in Figure 2 but the points represent a number of individual observations. The distribution of these points gives an idea of the extent of agreement between different observers. The curve is not intended to be the best curve through the points but is based on illustrative assumptions used in Chapter 9.

3. This ideal curve of noise at 25 kc seems to rise rather rapidly between 20 and 30 knots and thereafter to rise more slowly. As will be indicated in the next chapters this rapid rise probably represents the development of propeller and other cavitation, which is the dominant source of noise in this region. Above 30 knots the machinery noise becomes dominant again and continues to rise, while the cavitation noise remains constant or even falls off a little. Below 20 knots it is probable that individual differences between torpedoes make it more difficult to make the same kinds of generalization. It is also probable that at lower frequencies the individual characteristics of torpedoes are more significant.

4. The noise level of all torpedoes seems to fall off roughly 6 db per octave. This indicates that the noise is inversely proportional to the square of the frequency, above 10 kc. This again is in rough agreement with observations on ships, so that there is probably no advantage from this point of view in selecting one frequency rather than another. Although the self noise falls off as the frequency is increased, the target noise, for a listening torpedo, falls off also, and at about the same rate. Two other factors, however, need some consideration. One is that the hydrophone discrimination to be discussed in Chapter 6 probably increases as the frequency rises so that the use of a higher frequency may produce an improvement in signal-to-noise ratio. On the other hand, the attenuation increases rapidly with frequency from somewhere around 4 db per kilometer near 25 kc to around 14 db per kilometer near 60 kc.

The question of the best frequency to use has not been at all thoroughly investigated. In the following discussion of self noise attention will be centered on the 25-kc region, since most of the work has been done there.



## Chapter 4

# CAVITATION AND CAVITATION NOISE

### 4.1 THE NATURE OF CAVITATION

THE PHENOMENON of cavitation gets its name from the fact that there is a production of actual cavities in the water. There may be a few large cavities or a large number of very small cavities, either attached to the surface of moving bodies or free in the water stream itself. Noise is nearly always associated with the phenomenon of cavitation. The exact mechanism is still obscure, but either the production of the cavities, the vibration of the cavities, or possibly the collapse of these cavities as they move into a region of higher pressure provides one of the most important sources of the underwater noise associated with a torpedo. For this reason, it is important to have some knowledge of the conditions under which cavitation occurs.

Cavitation is essentially a phenomenon of liquids. It occurs at points in the liquid where the pressure of a perfect incompressible fluid would become negative. In reality, it is only necessary that the pressure fall below the vapor pressure of the liquid, for then the liquid opens up in small cavities that are immediately filled with vapor. On this picture, it is clear why cavitation does not occur in gases. If an attempt is made to reduce the pressure of a gas below zero, the gas merely expands. No matter how much the volume is enlarged, the gas continues to expand and fills the whole available space. Water, on the contrary, does not expand very much when the pressure is reduced, but instead it evaporates to fill the available volume with water vapor. In many cases the pressure of water vapor is insignificant compared with other pressures involved. In such cases the vapor pressure may be neglected, and it may be considered that an attempt to reduce the pressure of a liquid below zero results merely in the creation of a vacuum.<sup>a</sup>

#### 4.1.1 A Simple Case of Cavitation

A simple case of cavitation can be observed when water flows through a tube of diminishing cross sec-

<sup>a</sup> It is true that under suitable conditions, liquids such as water can support a considerable tension. Under the circumstances with which we are concerned, however, in which the water is not particularly pure and in which solid surfaces are moving through the water, this possibility of tension may be ignored, and it may be considered that a reduction of pressure to the vapor pressure of the water or below will always result in cavities.

tion. Since the cross section is diminishing, the velocity of the water is increasing and, according to Bernoulli's theorem,

$$p + \frac{1}{2}\rho v^2 = \text{constant.} \quad (1)$$

The pressure must decrease as the cross section diminishes because the pressure must decrease as the velocity increases. In equation (1) the pressure is measured in pounds per square foot, the density in slugs per cubic foot, and the velocity in feet per second. In these units, the density of water is approximately 2, so that a velocity of 50 fps corresponds to a reduction of pressure of about 2,500 psf, or more than an atmosphere. If the pressure is one atmosphere where the water has a negligible velocity, cavitation will occur down the stream where the velocity approaches 50 fps.

#### 4.1.2

### Vortex Cavitation

Another situation under which cavitation may occur is associated with rotational motion of the water and the accompanying centrifugal force. As an illustration of the kind of thing that can occur, one may consider a simple vortex, at the center of which pressure will be a minimum. This can be understood by considering an idealized vortex consisting of the rotation of a cylindrical volume of water whose radius is  $R$ , at a constant angular velocity  $\omega$ . The velocity at any point inside the cylinder is then given by

$$v = \omega r,$$

where  $r$  is the distance from the center of the cylinder. Outside of this cylinder the motion is "irrotational," even though the water is moving about the central cylindrical core. This is possible if the velocity is inversely proportional to  $r$ . These two motions give the same velocities at the radius  $R$ , if the constants are properly selected. Hence let us assume that

$$\text{for } r < R, \quad v = \omega r = \left( \frac{K}{2\pi R^2} \right) r,$$

$$\text{for } r > R, \quad v = \frac{\omega R^2}{r} = \frac{K}{2\pi r}.$$

The significant measure of the strength of this vortex is the quantity  $K$  that is called the circulation.



Outside the central cylinder of radius  $R$  the motion is "irrotational," and Bernoulli's theorem can be used to determine the pressure in terms of the pressure at great distances from the vortex. This leads to

$$p = p_{\infty} - \frac{\rho}{2}v^2 = p_{\infty} - \frac{\rho \left(\frac{K}{2\pi}\right)^2}{r^2}.$$

For  $r < R$ , the analysis shows that

$$p + \frac{\rho}{2}v^2 = p_{\infty} - \rho \left(\frac{K}{2\pi R}\right)^2 + \rho v^2,$$

whence

$$p = p_{\infty} - \rho \left(\frac{K}{2\pi R}\right)^2 + \frac{\rho}{2} \left(\frac{K}{2\pi R^2}\right)^2 r^2.$$

At the center of the core the pressure is

$$p_0 = p_{\infty} - \rho \left(\frac{K}{2\pi R}\right)^2. \quad (2)$$

This pressure depends both on  $K$  and  $R$ . It depends both on the strength of the vortex  $K$  and the extent of the vortex  $R$ . For a given value of  $K$ , the pressure becomes lower if  $R$  is made smaller. It is clear from this form of expression that it is quite possible for the pressure  $p_0$  at the center of the vortex to become negative, and hence for these equations to fail to describe the physical situation. Under such conditions, a cavity will open up at the center, and cavitation will occur. Figure 1 shows the way in which the

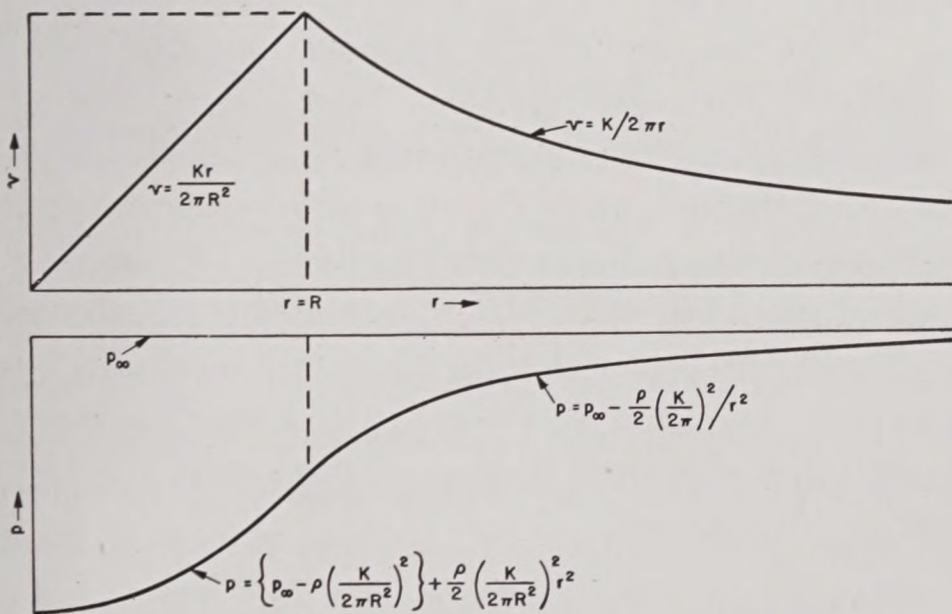


FIGURE 1. Speed of the water and the pressure plotted as a function of the distance from the center for an idealized vortex of a simple type.

pressure and the velocity depend on the distance from the center of a simple vortex of this kind.

The importance of cavitation in a vortex, when considering the self noise of a torpedo, comes from the fact that a trailing vortex is left behind the tip of

a propeller that is driving a torpedo through the water. If the circulation around this vortex is great enough, or if the vortex is concentrated enough ( $R$  small enough), cavitation will occur and will be a serious source of noise. Since the magnitude of the propeller thrust is associated with the circulation  $K$ , the only way to avoid cavitation and to maintain the thrust is to shape the propeller blade so that the vortex is not shed in a concentrated form but is spread out over a considerable volume. This means that the vortex will have very little similarity to the simple type of vortex described here, but will be much more complex. Nevertheless, the principle involved is that illustrated; since the vorticity cannot be reduced without reducing the thrust, efforts to reduce the cavitation of the propeller by suitable design must be directed toward getting the vorticity to occupy a volume greater than some minimum volume. A somewhat intensive study of this problem has been made at the Harvard Underwater Sound Laboratory [HUSL].<sup>22</sup>

Figure 2 shows a test propeller in a water tunnel at the David Taylor Model Basin [DTMB]. The cavitating vortices from the propeller tips can be clearly seen extending in helices down the stream. Only because the vortex is cavitating can it be seen.

#### 4.1.3

### Body Cavitation

When a solid body is moving through the water with a velocity  $V$ , the speed of the water with reference to the body has a variety of values at various points and at some places is considerably higher than  $V$ . At such points the pressure is lower than in the free water and may become low enough to initiate the phenomenon of cavitation. In this way, cavitation may occur in the neighborhood of a torpedo moving through the water quite apart from the cavitation that may exist in the propeller tip vortices.

As an illustration, consider the case of a sphere.<sup>2</sup> This is simple enough so that the flow of perfect fluid around it can be calculated. If the sphere is considered to be at rest and the fluid to be moving past this with a velocity  $V$ , the velocity at a point in the fluid outside the sphere is

$$\begin{aligned} v_r &= V \left(1 - \frac{R^3}{r^3}\right) \cos \theta, \\ v_\theta &= V \left(1 + \frac{R^3}{2r^3}\right) \sin \theta. \end{aligned} \quad (3)$$

The polar coordinates  $r$  and  $\theta$  are based on the center



of the sphere as the origin and the direction of flow as the polar axis.  $R$  is the radius of the sphere.

It follows from these equations that the point of maximum velocity is at the surface of the sphere,  $r = R$ , where  $\theta = \pi/2$ . At this point  $v^2 = 9V^2/4$ . Then according to Bernoulli's theorem,

$$p + \frac{9}{8}\rho V^2 = p_\infty + \frac{1}{2}\rho V^2,$$

and

$$p = p_\infty - \frac{5}{8}\rho V^2. \quad (4)$$

This gives the pressure around the equator of the sphere in terms of velocity  $V$ , as long as the motion of the water is described by the above expression. When the velocity is large enough, so that  $p$  becomes equal to the vapor pressure of the water, or approximately zero, cavitation will occur around the equator of the sphere. If the velocity is increased still further, the cavitation spreads over more and more of the sphere, and the equation ceases to give the correct description of the velocity of the water in the cavitation region. The type of calculation just indicated often serves to indicate the velocity at which cavitation will set in, but it does not serve to describe the further development of the phenomenon and the enlargement of the cavity.

#### 4.1.4 Cavitation Coefficient

If  $V_c$  is the velocity at which the cavitation just begins, the cavitation properties of the body may be described by a cavitation coefficient  $K_c$ . From equation (4) describing the pressure around the sphere,

$$\frac{p_\infty - p_v}{\frac{1}{2}\rho V_c^2} = K_c = 1.25.$$

This value of  $K_c = 1.25$  may be regarded as a statement of the susceptibility of the equator of the sphere to cavitation. It is important to notice that  $V_c$  is the velocity of the whole water stream with reference to the sphere and not the velocity of the water at the point where the cavitation begins.

Calculations of this type have been worked out to give the critical values of  $K_c$  for a number of different shapes. For ellipsoids of revolution whose major and minor axes are  $a$  and  $b$ , the following values were found to hold.

$\frac{a}{b}$	$K_c$
1	1.25
2	0.46
3	0.26
4	0.19

In addition the value for a simple, "half streamline" body turns out to be 0.33. These results indicate that in general, cavitation occurs more readily around a blunt body than around a somewhat pointed body.

#### 4.1.5 Propeller Blade Cavitation

A similar type of cavitation may also occur on the blades of a propeller, since these blades move through the water with a velocity considerably higher than the forward motion of a torpedo itself. A propeller blade is essentially a short hydrofoil moving through the water with a certain angle of attack, so that the pressure is increased on its face and decreased on its back. As the speed increases, this decrease of pressure becomes greater and greater and may eventually produce a pressure as low as the vapor pressure or lower. Under these circumstances, cavitation sets in as usual. This type of cavitation has been known for some time in connection with propellers, because it seriously reduces the efficiency of the propeller. The pressure of the water at some distance from the propeller blade provides a limit to the pressure reduction on the back of a propeller blade. If this limit is reached at one point on the surface of the propeller, further increase in propeller speed produces less additional thrust than it would otherwise do.

It is not difficult to calculate the pressure distribution over simple hydrofoils, but it is somewhat more difficult to make the calculation for an actual propeller. Nevertheless, after a propeller is built, it is possible to test it for cavitation and to observe the conditions under which the phenomenon occurs. Cavitation is of importance in ordinary propellers because of its effect on propeller efficiency, but it is far more important in the case of acoustic torpedoes because of the noise that it produces. This has led to an increased interest in the study of this phenomenon and of methods of reducing it. As will be shown later, however, to eliminate the noise it seems necessary to essentially eliminate the cavitation, not merely to reduce its amount.

#### 4.2 OBSERVATIONS OF CAVITATION

Figure 2 shows the way in which propeller tip cavitation can be observed in a water tunnel. If cavitation does not appear under normal operating conditions, it can usually be brought about by increasing the propeller loading or reducing the water pressure.

Extensive observations of body cavitation have been made in the High Speed Water Tunnel at the Cali-

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fornia Institute of Technology [CIT].<sup>3</sup> A small body of the shape to be studied was placed in the water stream and observed visually. Both the velocity of the water and its pressure could be varied, and it was

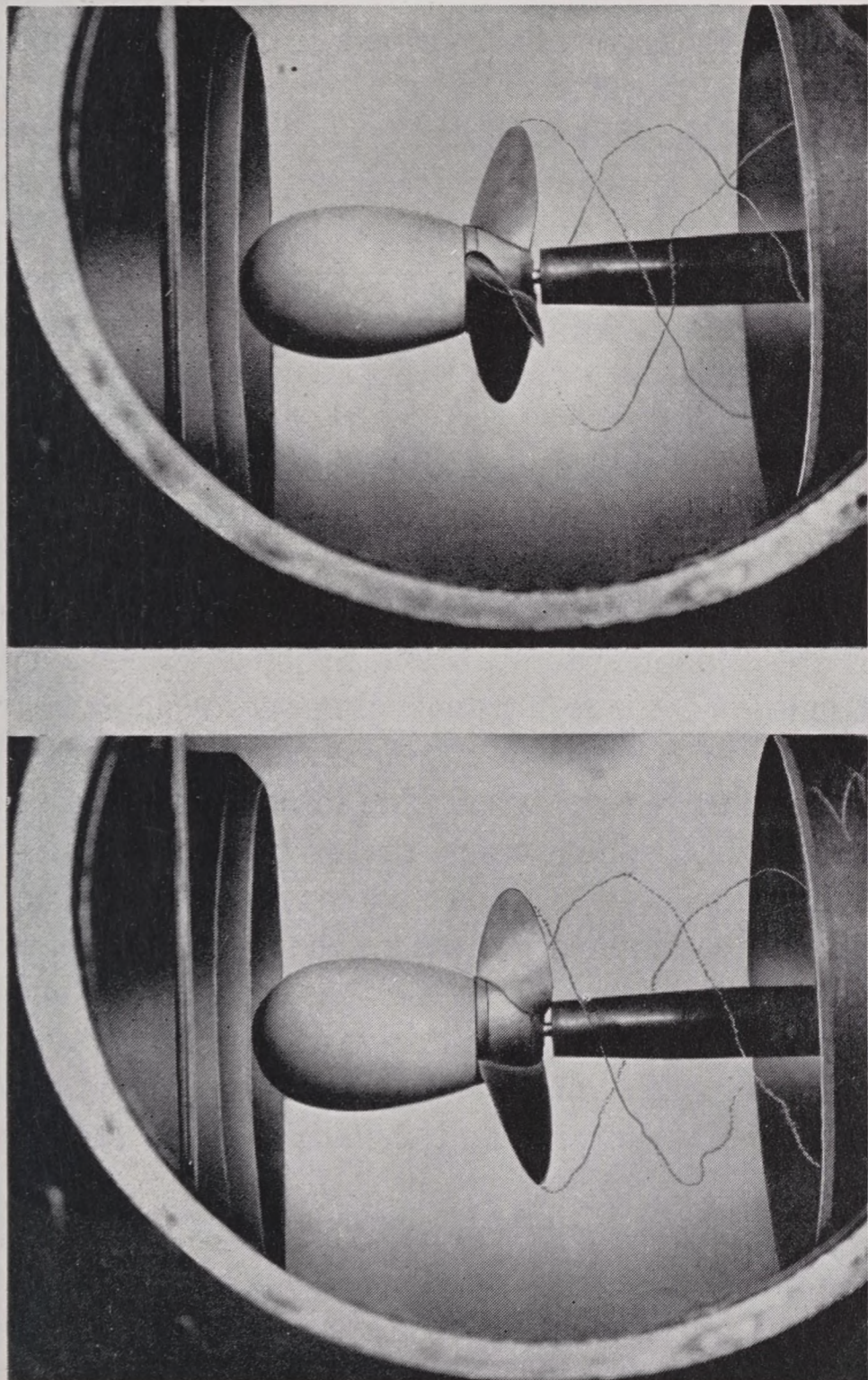


FIGURE 2. Photographs of a propeller in a water tunnel at the David Taylor Model Basin showing the cavitating vortices trailing from the propeller tips.

shown that a cavitation coefficient  $K_c$ , as defined above, could be attributed to various points on the body and would describe the conditions under which cavitation would appear.

In a slightly different sense a cavitation parameter can be used to describe the conditions under which a body is moving, or the conditions in the water tunnel. In this case the velocity is just the existing velocity. It can then be said that cavitation begins at a certain point on the body when the cavitation parameter is decreased below the value of the cavitation coefficient at the point.

Observations on a sphere gave  $K = 1.2$  as the point at which cavitation first set in. This is in ade-

quate agreement with the calculated value 1.25. On a cylindrical body with a hemispherical nose, cavitation was observed for  $K$  about 0.75. This observed value of 0.75 indicates that a torpedo of this shape running 15 ft deep, where the pressure is approximately 3,000 psf, would begin to cavitate at speed around 68.9 fps, or approximately 38 knots.

Since it may well be desired to run acoustic torpedoes at speeds greater than 38 knots, and possibly at depths less than 15 ft, it is important to have nose shapes that do not cavitate so easily. A number of other shapes were tried in the Water Tunnel, with the following results.

	Nose length Body diameter	$K_c$
Hemisphere	0.50	0.89
Ogive 1.125-cal radius	0.94	0.41
Ogive 2.0-cal radius	1.33	0.33
Ellipsoid	0.75	0.48
Ellipsoid	1.25	0.30
Half streamline with quartic transition curve	1.25	0.35

It must be noted that these values of the cavitation coefficient apply only when the torpedo is traveling in the direction of its axis, i.e., when the pitch and yaw are zero. At other values of the pitch and yaw cavitation tends to set in earlier. The elongated noses, in particular, are especially sensitive to yaw angles. Furthermore, other points on the torpedo show more pronounced tendencies to cavitate than the nose. In particular, the fins of the Mark 13 torpedo show a critical value of  $K_c = 0.93$  at zero yaw, and  $K_c = 1.6$  at 4 degrees yaw. Hence the problem of designing a torpedo to travel at high speeds without cavitation presents a number of difficulties. The torpedo will nearly always yaw and pitch to some extent, and it will certainly travel with a yaw angle if it is expected to turn in a small circle. Those shapes that tend to postpone cavitation to high speeds when traveling in a straight line tend also to produce cavitation easily when moving at an angle to their axes.

Observations were also made at the High Speed Water Tunnel concerning the cavitation on an airfoil section.<sup>3</sup> They show quite clearly the dependence of the critical cavitation parameter on the angle of attack, and hence on the thrust exerted by a propeller.

Studies have also been made by HUSL of propeller cavitation in a model propeller tunnel. This work showed that the incidence of cavitation could be described in terms of a cavitation parameter in the same way as cavitation about a torpedo nose. There



are various cavitation parameters that might be used in connection with a propeller. One of these uses the propeller tip speed as the significant velocity. On the other hand, it is true, of course, that those parts of the propeller blade close to the axis do not have so high a speed as the tips and hence the speed of the hydrofoil section is not always the same as tip speed. Another method is to use the forward speed of the propeller through the water. This at least is the same for all parts of the propeller and is roughly proportional to the propeller tip speed. It is probably of little importance which cavitation parameter is used, as long as its significance is recognized. If the forward speed through the water is used, cavitation will occur at rather large values of the cavitation parameter, because the propeller tips will be moving at a considerably higher speed than the speed used in the parameter.

The HUSL observations indicated that propeller tip cavitation usually set in first, and that later cavitation on the blades could be observed. Similar observations have been made at the DTMB propeller tunnel.

#### 4.3 NOISE DUE TO CAVITATION

The principal importance of cavitation in the design of acoustic torpedoes is due to the noise produced. It is now quite clear that cavitation, even barely incipient cavitation, is a major source of noise, but the detailed mechanism of its production is not at all clear and much work remains to be done before quantitative relationships can be established between the intensity and character of the noise and the properties of the cavitation.

When the work on underwater sound was first inaugurated in the University of California laboratory at Point Loma, some preliminary exploratory work was started at Berkeley.<sup>4</sup> It was hoped in this way to get some general indication as to the way noises are produced under water. The general conclusion was that the noise associated with breaking the surface of the water or with cavitation was greater in order of magnitude than that produced in any other way. The noise produced by moving rough surfaces through the water was almost negligible compared with that due to any kind of a surface disturbance. This is in conformity with general observation that ambient noise in the sea increases sharply as white-caps appear.<sup>5</sup>

In an effort to make a start on a study of the rela-

tionship between cavitation and noise, a hydrophone was installed in the High Speed Water Tunnel at CIT. With this hydrophone, observations were made of the noise level as a function of the cavitation parameter for a number of different torpedo and bomb models. This work is described in detail in a report from this laboratory.<sup>6</sup>

One of the major difficulties in the use of a water tunnel for noise measurements of this kind is the large amount of noise produced by the tunnel itself. The pumping machinery is noisy, and the noise is easily transmitted to the working section. This background noise also varies with the speed and pressure of the water. Nevertheless, it was found in confirmation of the expectations, that the noise produced by cavitation on a model so outweighs the other noises that it can be clearly recognized.

Another difficulty is the fact that the cross section of the tunnel in the working region is rather small. The measurement of sound intensity in such a space is difficult because of interference phenomena and reflection from the walls. The intensity measured is strongly dependent upon the exact position of the hydrophone as well as on its orientation. It is practically impossible to get a significant measure of absolute sound intensity under these conditions, but it is possible to get a qualitative idea of the way the noise sets in sharply with the incidence of cavitation, rises to a maximum, and then falls off as the cavitation builds up.

To produce cavitation easily, a model was used in which the nose was flat. This was produced by cutting off a hemispherical nose at something like three-fourths of its radius. Under these conditions, cavitation set in at  $K = 2.6$ . Figure 3 gives an idealized curve for this case. As the velocity of the water is increased, or the pressure is reduced, so that  $K$  passes through the value 2.5, the sound intensity increases sharply by over 20 db. It then continues to rise more slowly as  $K$  is decreased but finally reaches a maximum.

Because of the difficulties indicated above, there may be a good deal of question as to the validity of detailed conclusions from this type of work. Nevertheless, several points stand out. It is most striking that the increase in noise level is coincident with the onset of cavitation. In other curves given in the report, the increase is not so sharp and it may be that the sharpness of this rise is associated with the shape of the body. Nevertheless, this principal conclusion is clear that cavitation produces noise, and that the



noise sets in rather sharply as the cavitation begins.

Another point indicated in Figure 3 is that further decrease of the cavitation parameter is associated with a decrease in the intensity of the noise rather

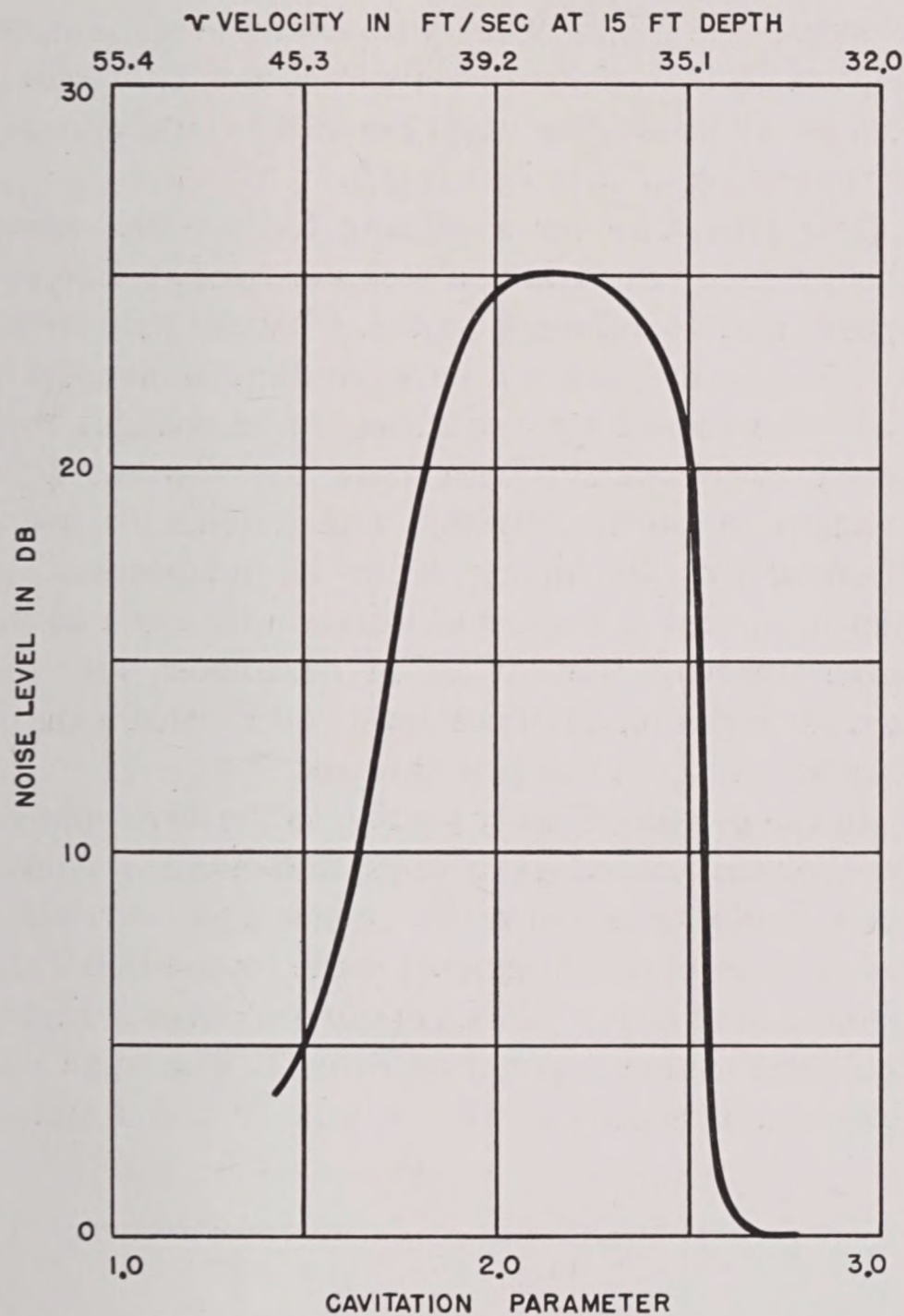


FIGURE 3. Idealized curve of cavitation noise as a function of the cavitation parameter for the case of a flat-nosed projectile. The sound levels are in decibels above the background.

than a continued building up. This seems to be observed quite generally in work with models and in other experiments designed to study the noise due to cavitation. Various suggestions have been made to explain it, but none of them are as yet supported by adequate experimental evidence. These suggestions include (1) the idea that the increasing cavitation tends to absorb the noise and prevent its reaching the hydrophone; (2) the idea that the noise is produced against the surface of the body itself rather than throughout the entire volume of the cavitation; and (3) the idea that the noise is produced downstream where the bubbles collapse and that this dis-

tance is greater for highly developed cavitation than at the beginning.

Some indications from the work in the High Speed Water Tunnel point to the possibility that the noise is not a function of the cavitation parameter alone, but of the velocity and the pressure separately. The evidence on the point, however, is so uncertain that it seems best for the present to regard the cavitation noise as a single valued function of the cavitation parameter.

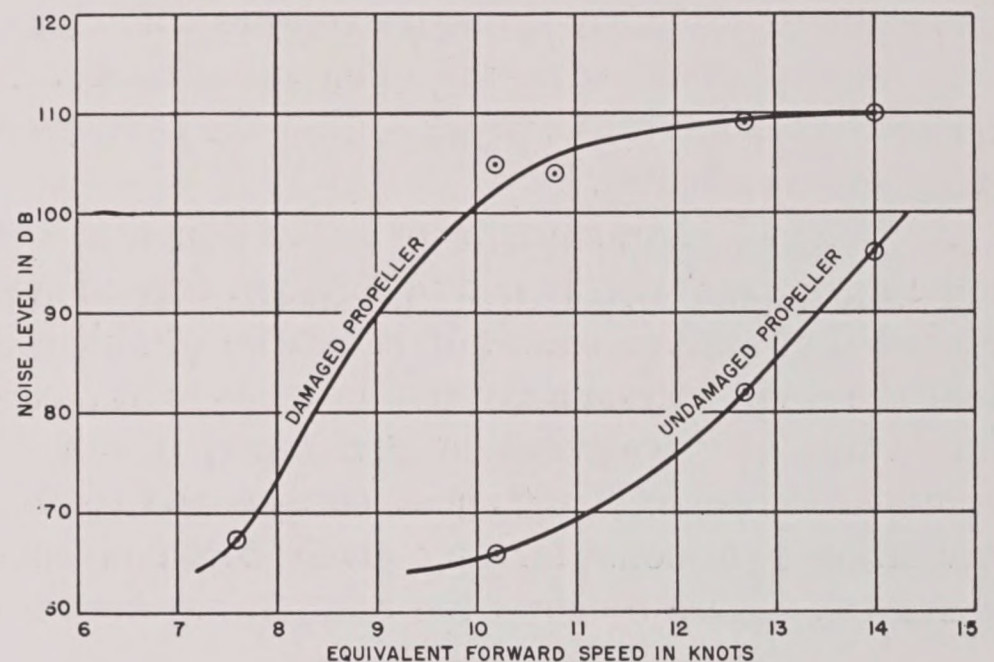


FIGURE 4. Sound levels in the propeller tunnel of the David Taylor Model Basin showing the effect of a small nick in the propeller.

Figure 4 represents some observations from the propeller tunnel at DTMB. For this work the pressure was kept constant and the speed of the water past the propeller was varied at the same time that the propeller rpm was varied. The hydrophone in the water tunnel showed a distinct rise in noise level at a fairly definite velocity, and this was approximately coincident with the beginning of cavitation.

The difference between a good propeller and a propeller having a nick in the blade is made very clear in this figure. Cavitation could be observed at the blade defect at a rather low speed and when it was observed, the noise was very loud.

In the work carried on by HUSL, noise measurements could be made only at very low speeds but, under these circumstances, the noise was observed to increase very rapidly just before tip cavitation could be seen.

#### 4.4 CAVITATION NOISE IN TORPEDOES

A good illustration of the character of the cavitation noise is given by a series of observations made on the ExF42 mine at DTMB. In this work the mine was attached to the strut supporting it from the



high-speed carriage. The motor in the mine was then driven at such a speed as to furnish the power necessary for the propulsion of the mine, while the carriage itself provided the power to drag the strut through the water. A hydrophone was placed in the towing channel so that the mine would pass over it at a distance of a few feet. The maximum reading of the sound intensity at the hydrophone was then taken as a measure of the noise produced by the mine and its propeller. The noise increased very little up to a speed of almost 15 knots. But at this speed it rose almost discontinuously through a considerable range. This was observed with the mine submerged 4 ft under the surface of the water so that the cavitation parameter is about 3.8.

A principal characteristic of cavitation and the noise associated with it is its combined dependence on pressure and on speed. If it can be established that the cavitation on a given object sets in at a certain value of the cavitation parameter, it can be readily determined what speed corresponds to this cavitation parameter for any given depth of submergence. Figure 5 shows the relationship between

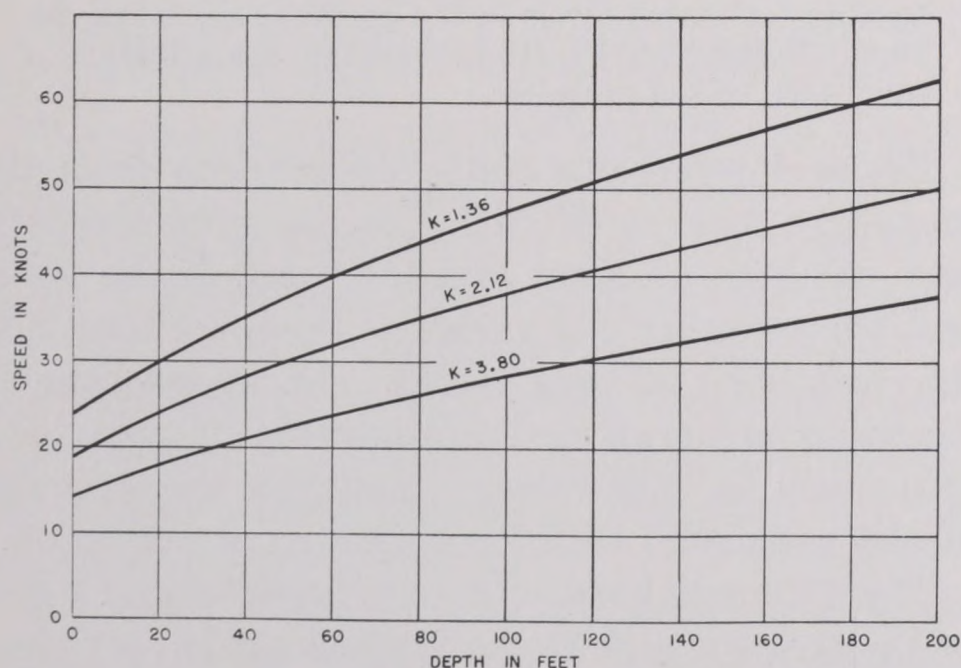


FIGURE 5. Speed in knots at various depths corresponding to several values of the cavitation parameter.

the cavitation speed and the depth of submergence in feet for three values of the cavitation parameter. Since it was found that the ExF42 mine began to cavitate at 15 knots when 4 ft deep, it follows from the lower of the three curves that at 120 ft deep, it could be driven at over 30 knots before cavitation sets in. The other two curves in the figure represent other possible situations in which the critical cavitation parameter is somewhat lower than that for the ExF42 mine. It must be remembered, of course, that this conclusion is valid only in case the speed of

all parts of the torpedo are proportionally increased. It is assumed that the propeller turns twice as fast to give 30 knots as to give 15 knots. This is of course not strictly true, since the propeller efficiency depends on the speed.

Cavitation noise can be identified by the way in which it varies with depth. If cavitation noise is present, the noise level will decrease at greater depths. In fact, if the principal noise of a torpedo is due to cavitation, this noise can always be eliminated by operating at sufficient depth.

The procedure for analyzing torpedo self noise, then, consists in making a series of runs at different speeds and at different depths. Changes with depth at a constant speed can be attributed to changes in the noise caused by cavitation, while changes with speed at constant depth must be attributed to changes in both cavitation and machinery noise. Presumably, machinery noise is independent of depth, so that if a series of runs can be made at the same value of the cavitation parameter, any observed variation in noise level with speed can be attributed to the machinery noise.

In the process of study leading to the development of acoustic torpedoes various measurements have been made that show the presence of cavitation noise. A set of measurements made by the Bell Telephone Laboratories [BTL] in the process of studying the ExS13 mine is given in Table 1. The mine was operated at speeds of 12, 16, and 20 knots and at

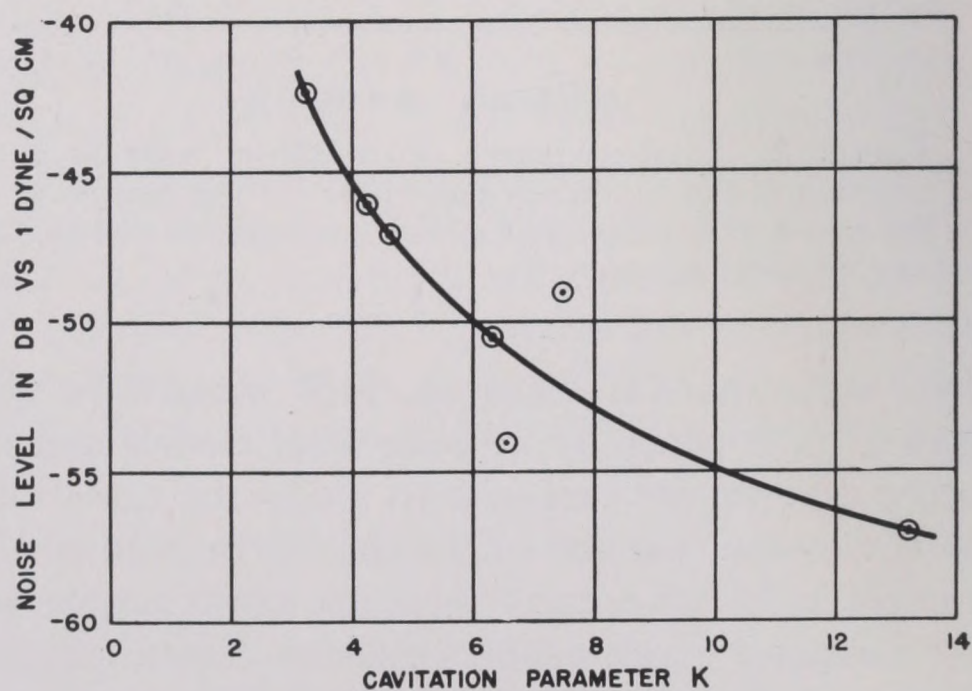


FIGURE 6. Self noise of the ExS13 mine plotted as a function of the cavitation parameter.

depths ranging from 10 to 80 ft. The data indicated are plotted against the cavitation parameter in Figure 6, where they fall on a smooth curve within limits

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TABLE 1.7 Measurements of the self noise of an ExS13 mine in a band near 24 kc. Level measurements are in dbs above 1 dyne per sq cm.

S P E E D		Depth feet	Cavitation parameter $K$	Noise level db
knots	ft per sec			
12	20.3	10	6.58	- 54.0
12	20.3	52	13.2	- 57.0
16	27.0	16	4.30	- 46.0
16	27.0	52	7.46	- 49.0
20	33.8	10	2.41	- 39.4
20	33.8	25	3.25	- 42.4
20	33.8	50	4.65	- 47.0
20	33.8	80	6.33	- 50.5

of experimental error. Since these measurements were made over an extended period of time, and since the machinery noise may change from one run to the next, some variations due to unknown causes are to be expected. In spite of these, the evidence points to the conclusion that at depths less than 50 ft the ExS13 mine, running at 20 knots, was producing essentially cavitation noise.

Numerous other examples of measurements that show the presence of cavitation noise are given in Chapter 10.



## MACHINERY AND OTHER NOISE

IN ADDITION to cavitation, the machinery in a torpedo is an important source of noise. At first thought it might be expected that the machinery would be the principal source of noise, for a torpedo running out of the water sounds like a tractor. In fact, in high-speed torpedoes the engine and gear noise may dominate the cavitation, but it seems that for torpedoes operating between 20 and 30 knots the cavitation and the machinery noise are of nearly the same order of magnitude. This has made the problem of identifying the source of the noise especially difficult. Cavitation noise can be reduced by going to greater depths, but if the cavitation and the machinery noise are approximately equal in magnitude, the reduction of one does not greatly reduce the total.

The only way to identify machinery noise is to eliminate it. This requires a slow process of trying one thing after another until some method of sound isolation is found that significantly reduces the total noise; and this must be done after it is fairly certain that the cavitation noise has been effectively eliminated by going to an adequate depth. Extensive studies of this kind have been made by the Harvard Underwater Sound Laboratory [HUSL] and some studies of motor isolation have been made by the Bell Telephone Laboratories [BTL]. This work gives general indications as to some aspects of the machinery noise but it is far from giving complete information on the subject and much important work remains to be done.

## 5.1 GEAR NOISE

Meshing gears are a troublesome source of noise in all torpedoes containing them. In the standard torpedo with counter-rotating propellers the main reversing gears seem to be possibly the dominant source of noise. Of the weapons with a single propeller, the Ex20F contains no important gear trains, but in the ExFF3 and the ExF42 mine the rudders are driven by high-speed motors through a train of reducing gears. In these cases there are indications from the noise measurements that the steering motors and gears fix the background level at about -57 dbs in the neighborhood of 24 kc. This low value is only attained by careful selection of the equipment, and the levels will frequently be much higher when an acoustic test is not used as a basis for gear inspection.

Extensive studies of the main reversing gear problem have been made by HUSL<sup>8</sup> and show clearly that much noise is due to this source. They investigated various gear forms and various gear materials and were able to produce some reduction in noise. The most effective procedure however, appeared to be an isolation of the gear system from the shell. Two effective methods seemed to be (1) an isolated gear housing and (2) an isolated idler gear.

The gear housing encloses the gears and keeps them away from the water. The housing is then isolated from the shell by a thick layer of Fairprene.

The isolated idler gear is a much simpler arrangement in which the idler gear shaft is not mounted directly on the shell but is isolated from it by a thick block of Fairprene. Figure 1 shows schematically how this is done, and shows the simplicity of such a modification for the Mark 18 torpedo.

The work on these gears has been done principally on the Mark 18 torpedo. This appeared to be a particularly promising object of study for the following reasons.

1. It was at first expected that an electric motor would be a quieter mode of propulsion than a steam turbine but the measurements mentioned in Section 3.2 showed this not to be the case. It might be suspected on this account that the gears were dominating at least the machinery noise.

2. The gears in the Mark 18 are open to the sea water and fairly independent of the balance of the power plant. This makes their modification a relatively simple problem and permits a study of the wide variety of suggestions necessary in this kind of work.

The measurements made by HUSL indicated that at a depth of 50 ft, where presumably the cavitation was suppressed and the gear noise was dominant, the isolated idler reduced the effective noise level at 25 kc from -29 to about -44 dbs. This is a very significant reduction and makes the Mark 18, at this depth, suitable for acoustic control.

Since the reversing gears appear to be such an important source of noise one might think it better to use only a single propeller and no gears. However, for torpedoes running at speeds much above 20 knots it is almost essential to use two counter-rotating propellers. This is true for two reasons.

1. It is very difficult to balance the torque of a single propeller because a torpedo is essentially



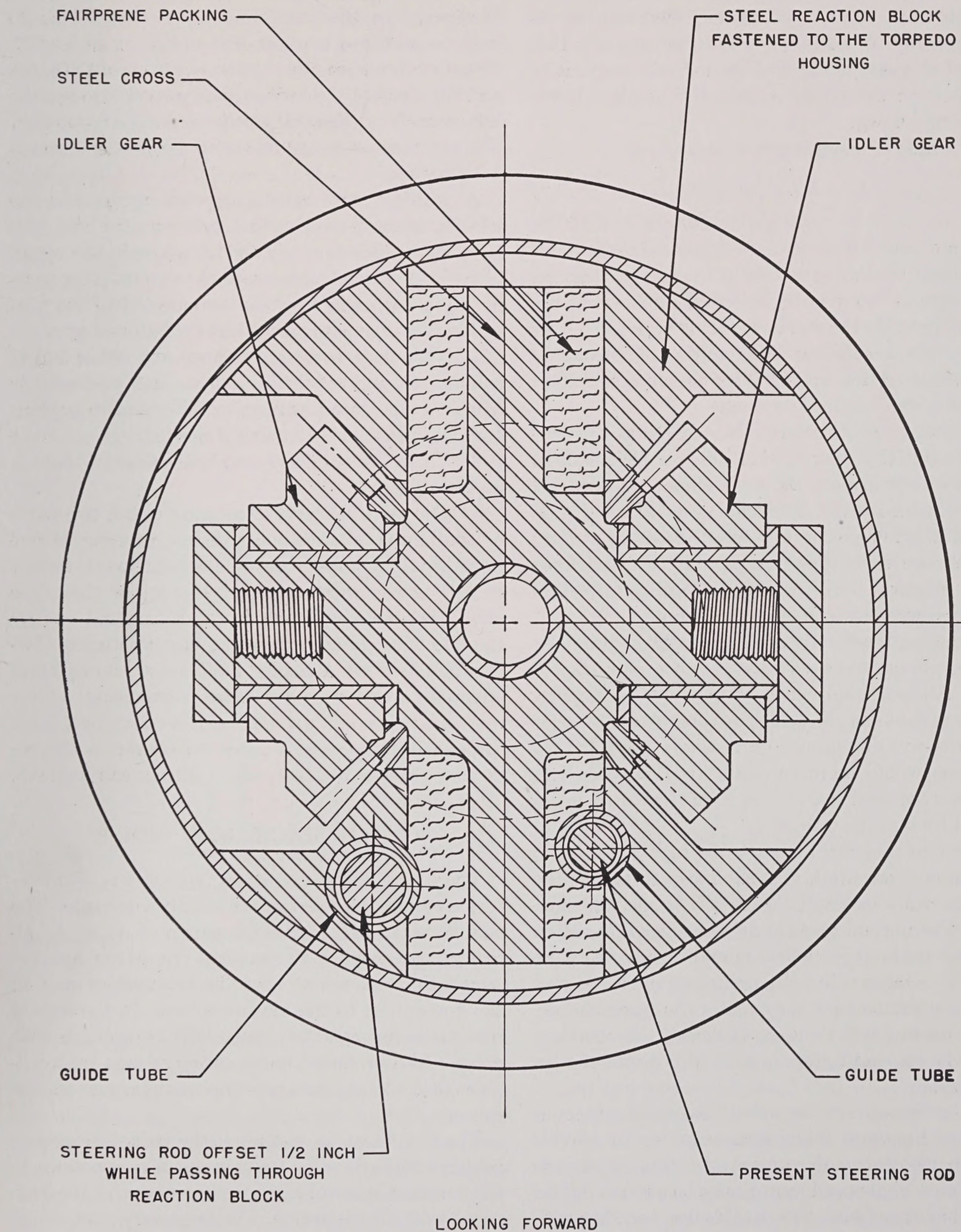


FIGURE 1. A method of idler gear isolation for the Mark 18 torpedo.

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cylindrical. It is possible to put some of the elements off center to create a stabilizing moment, but there is a limit to the amount of moment that can be created this way. In addition, when the torque is balanced in this way the heel of the torpedo is critically dependent on the power output and changes if the motor slows down.

The torque of a single propeller is given by

$$L = 5,250 \text{ hp/rpm}$$

so that for 180 hp at 1,600 rpm the torque is 592 ft-lb. This is not easy to balance by shifting weights even if the torpedo is allowed to heel as much as 45 degrees.

The torque can also be balanced by skewing the fins, and possibly the rudders and elevators also, to a proper angle and the necessary angle will be roughly independent of the speed. This method, however, introduces some additional drag.

In addition to the torque necessary for steady running, the initial acceleration of the propeller tends to turn the torpedo past its equilibrium position and may well turn it over. Problems of this kind can be handled in a low-power, low-speed torpedo but they become more difficult as the speed is increased. Possibly a practical limit for single propeller torpedoes lies somewhere between 20 and 25 knots.

2. The load per unit area on a single propeller must be almost twice as great as on a pair of propellers. Although only entirely inadequate information is available on the properties and characteristics of counter-rotating propellers, it seems probable that cavitation would be more easily avoided when two propellers are used than when all of the thrust is developed by a single propeller.

Since two propellers seem to be highly desirable, if not almost essential, it is necessary to isolate the gears carefully or else to drive the propellers separately. The normal torpedo drive has been based on the idea that both propellers should turn at the same speed. This means that the propellers must be carefully balanced so that they apply the same torque. To the extent that they are balanced the resultant torque is zero and the torpedo will travel on an even keel.

For turbine-driven torpedoes the gear system is necessary for speed reduction as well as to provide the two directions of rotation. In case of electric torpedoes a high-speed motor may be enough lighter than a low-speed motor so that its use, together with the reducing gears, is advantageous. If these systems are used, some kind of gear system is necessary.

However, it is possible in electric torpedoes to drive each propeller separately. This was done by the Westinghouse Electric Company in their Mark 26 torpedo and also in their first model of an ExS29. These motors were mounted one in front of the other and the shaft of the forward one passed through the hollow shaft of the after motor to the after propeller. The after motor drove the forward propeller through a hollow shaft.

A possibly more satisfactory arrangement is the use of a counter-rotating motor. In this the field coils turn in one direction and the armature in the other. The torque is applied between the two rotating parts of the motor, each of which is connected to one propeller. This system has a number of advantages.

1. There is no torque to compensate, either during running or during starting, so a small metacentric height is adequate to insure stability and to prevent heel. No propeller balancing is needed.

2. There are no gears and consequently there is no gear noise.

3. The relative speed of rotation of the two parts of the motor is twice the speed of rotation of one propeller. This makes possible a high-speed, lighter weight motor without gears. Motors of this type have been built by Stone & Co. of England and by the Electrical Engineering and Manufacturing Corporation of Los Angeles. Tests have shown their advantages with respect to torque balancing.

As a conclusion it may be repeated that for a quiet torpedo it is necessary either to eliminate the reversing gears or to isolate them. Either can be done.

## 5.2 OTHER MACHINERY NOISE

There are numerous other possibilities of interference from the mechanism within a torpedo. The control apparatus is often a source of noise. As already mentioned, if the rudders are driven by electric motors through a gear train, this system may set the lower limit to the self-noise level. In the case of pneumatically operated controls it is probable that noise is also produced but no observations are available that clearly indicate the significance of this source.

The reciprocating engines of the British torpedoes produce vibrations of frequencies corresponding to the number of revolutions per second and the harmonics of this frequency. The frequency with which the propeller blades pass the rudders may also appear in the noise spectrum of a torpedo.

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Apparently the commutator and brushes of a d-c motor produce a significant noise. This is apparently transmitted to the hydrophones by way of the shell. Either it is transmitted through the shell directly or is radiated by the shell into the water and then is picked up by the hydrophones. Probably neither statement is an adequate description of the interrelated action of the shell and the surrounding water in transmitting this noise, but in any case isolation of the motor from the shell seems to reduce its effect.

In the process of studying the isolation of the motor from the shell, BTL made a series of observations that led to the conclusion that some types of isolating material were quite effective in inhibiting the transmission of shear vibration but were relatively ineffective against compressional waves. In such a case it was possible to construct a type of mounting in which two isolating layers were provided at right angles to each other. Figure 2 shows schematically the idea involved.

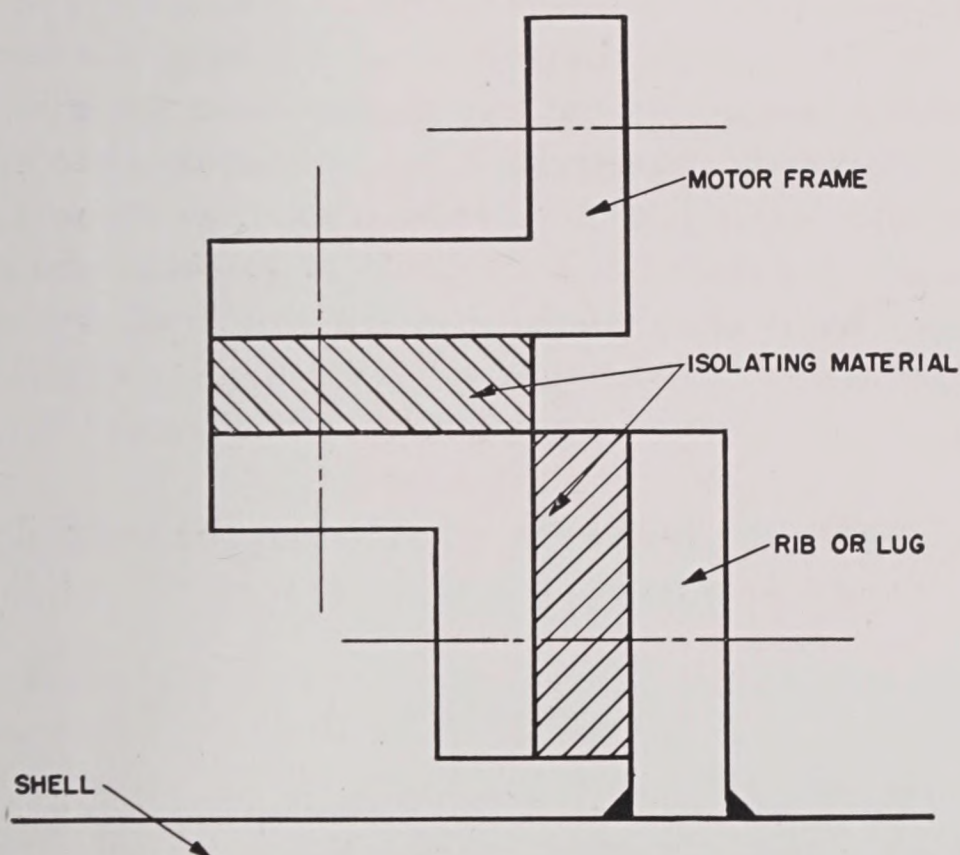


FIGURE 2. A schematic illustration of a method of using a material that isolates against shear vibrations only.

In general it seems that machinery noise has rather well-defined frequencies in the low-frequency region, below 5,000 c, but that at high frequencies the various harmonics are so close together that it is not significant to speak of individual frequencies. At lower frequencies it might be possible to place a sharply tuned hydrophone at a frequency between the characteristic frequencies of the machinery noise. It would be very difficult, however, to specify a manufacturing procedure that would guarantee satisfac-

tory discrimination in all cases. The general procedure thus far has been to use a moderately high frequency where the exact frequency is of less importance and where the variation in effective noise level from one torpedo to the next can be kept within reasonable limits.

### 5.3 NOISE DUE TO GAS FLOW

Very probably the passage of high-pressure air through restrictions and valves produces a certain amount of high-frequency noise that can be troublesome. This can possibly be controlled by isolating the pipes and fittings from the shell carrying the hydrophones. In general it seems that very little noise of this type is carried through the air but it is very effectively transmitted by metallic contact.

The emission of gas into the turbulent boundary layer surrounding a torpedo may well produce a good deal of high-frequency noise. Experiments in which an ExF42 mine was propelled by a sea water battery from which gas was exhausted through an opening in the top showed a noise level over 15 db above the normal running noise. This was almost as much as produced by propeller cavitation.

### 5.4 OTHER SOURCES OF NOISE

Although noise due to cavitation and noise associated with the machinery constitute the principal types of torpedo noise, there are some other types that may be of importance under certain circumstances. These have been the object of only a limited amount of study, and the following comments are essentially indications of subjects for study.

#### 5.4.1 Water-Flow Noise

In some cases it appears that the turbulent surface layer of water flowing over a hydrophone produces an effect that is principally noticeable in the lower frequencies, below 3,000 c. This seems to be analogous to the phenomenon of "windage" in which a wind blowing over a microphone may produce a considerable response, although the noise radiated into the air is negligible.

Water-flow noise produced in this way would not be picked up in an external hydrophone but it might well contribute to the response of a hydrophone mounted in the body and must be considered as a possible source of self noise. Presumably it can be avoided by shielding the hydrophone itself from



direct contact with the moving water, or possibly by placing it near the nose where the turbulent surface layer has not had a chance to develop.

Some observations have been made on this type of noise by BTL<sup>9</sup> but it does not seem to be of significance above the audible range of frequencies.

In some cases it appears that the impact of the water on parts of a torpedo may set up resonant vibrations. If a stream of water is incident on a tuning fork held under water, the fork is set into vibration and the sound is radiated through the water. Normally the resonant frequencies that are not too highly damped are in the acoustic range and not much above it.

Both of these kinds of water-flow noise need more study before appraisal of their significance is possible. However, on the basis of preliminary indications, it

seems that the higher the frequency the less they are of importance.

#### 5.4.2 **Propeller Vibration**

During some of the studies of experimental bodies of the type of the ExF42 a rather loud whine of about 2,000 c was observed. Studies of the propeller showed a natural frequency of vibration near 2,200 c which changed to 2,000 when the propeller was immersed in water. Apparently this vibration was excited either by the motor through the propeller shaft, or by the water forces. Various methods were tried by BTL<sup>10</sup> for reducing this vibration and it can probably be controlled. However, again it is fortunate that vibrations of this kind will probably be confined to the region of acoustic frequencies and can be avoided by working in the supersonic region.



## HYDROPHONE DISCRIMINATION AND ISOLATION

IN CONSTRUCTING an acoustically controlled torpedo the effective noise level can be reduced just as well by reducing the response of the hydrophone to the background and self noise as by reducing the level of the noise itself. This must be done of course, without reducing the hydrophone response to the desired signal. For this reason it is convenient and customary to express the background and self-noise levels in terms of the intensity of the plane wave incident on the hydrophone from the direction of maximum sensitivity that produces the same rms response as does the noise.

When it is stated that the self-noise level is  $-20$  db, the meaning is that the electrical response of the hydrophone and its circuit has the same rms value as though a plane wave of intensity level  $-20$  db were incident on the hydrophone from the direction of maximum response. The cause of the response need not be sound, in the simplest sense, at all.

The self noise may be electric interference picked up by the circuit because of inadequate shielding. In many cases a large amount of the self noise appears as vibrations in the torpedo shell which are transmitted directly to the hydrophone so as to set it in vibration. In all cases it is equivalent to a noise and must be controlled for effective operation.

### 6.1 DISCRIMINATION AGAINST WATER BACKGROUND NOISE

Water background noise usually comes more or less uniformly from all directions, i.e., it is isotropic. A nondirectional hydrophone responds to the total sound intensity, regardless of direction. A directional hydrophone, on the other hand, responds only to sounds coming from certain directions and therefore responds less to an isotropic sound field than does the nondirectional hydrophone. This difference in response is described by the directivity index.<sup>11</sup>

If a hydrophone responds uniformly to sound incident within a solid angle  $\Omega$ , and has a zero response outside of this angle, then its response to an isotropic sound field will be  $(\Omega/4\pi)$  of that of nondirectional hydrophone. Its directivity index will then be

$$D = 10 \log \left( \frac{\Omega}{4\pi} \right),$$

and the response to an isotropic sound field whose level is  $L$  will be  $(L + D)$ . For purposes of reducing

the response to the water background noise it is desirable to have  $D$  as much negative as possible, i.e. to have the hydrophone sensitive in as small a solid angle as possible. Since, however, the water background is the limiting factor only in rather special cases, this is not a dominant factor.

The directional patterns of the ExF42 crystal hydrophone and the HUSL twelve-tube magnetostriction hydrophone are shown in Figures 1 and 2.

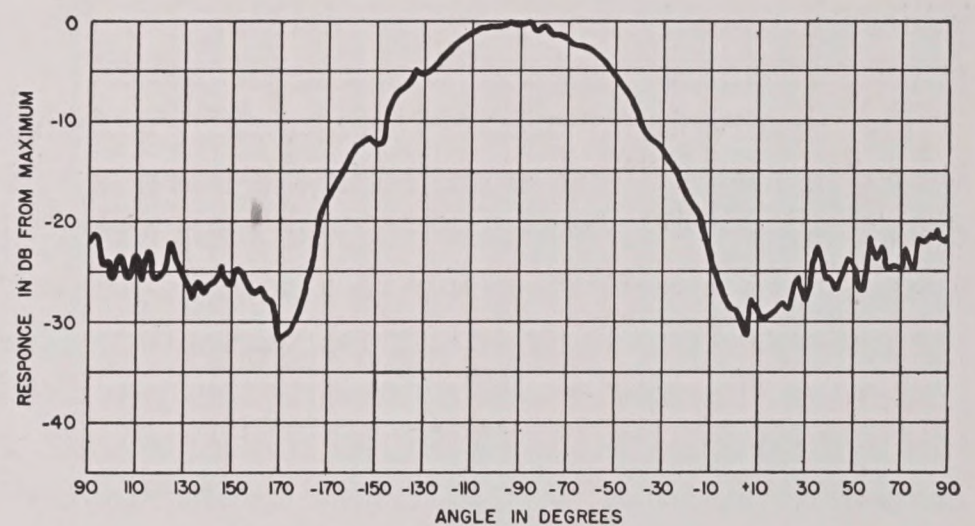


FIGURE 1. Directional response pattern of a crystal hydrophone as used in the ExF42 mine.<sup>12</sup>

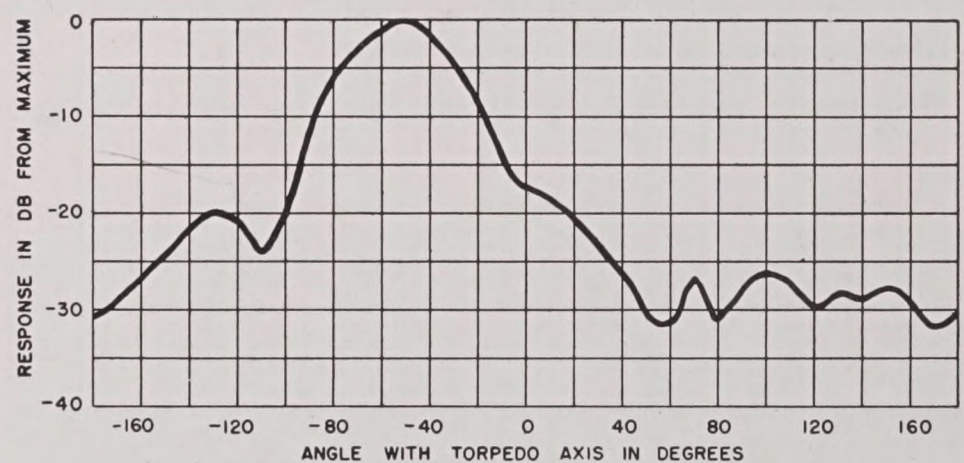


FIGURE 2. Directional response pattern of a 12-tube magnetostriction hydrophone.<sup>13</sup>

These patterns are not entirely independent of the hydrophone mounting, and the curves shown represent the hydrophone mounted in a portion of a torpedo body. The two directive indexes,  $-11.0$  and  $-13.6$  db, show that for an average background level of  $-54$  db at 25 kc the hydrophone responses will be about  $-65$  and  $-68$  db respectively. This is low enough so that it rarely compares with the other noises present.

For a given hydrophone and mounting, the directivity index becomes more negative as the frequency increases. This merely means that a given hydrophone is more directional for short wavelengths than for long. Since, in addition, the water noise level in general decreases at higher frequencies, the response



of a hydrophone to background noise falls off quite rapidly as the frequency increases.

## 6.2 DISCRIMINATION AGAINST CAVITATION

In most cases the principal cavitation around a torpedo is associated with the propeller. The noise from this cavitation is then transmitted partly through the water and partly through the torpedo shell to the hydrophone. Since the sound travels almost parallel to the shell, the distinction between these two modes of transmission is not sharp, but it indicates roughly two ways of making the hydrophone discriminate against the propeller noise.

The hydrophone whose directional pattern is shown in Figure 1 was mounted in the side of a cylindrical body. The response to the rear along the cylinder is about 27 db below that at right angles to the cylinder. To the extent, then, that a directional pattern of this kind really represents the response of the hydrophone to the cavitation noise around the propeller, one may say that this hydrophone discriminates against cavitation noise to the extent of 27 db. In the ExF42 mine this discrimination is apparently of little importance, since there is practically no propeller cavitation noise.

Figure 3 shows a pattern for the same type of

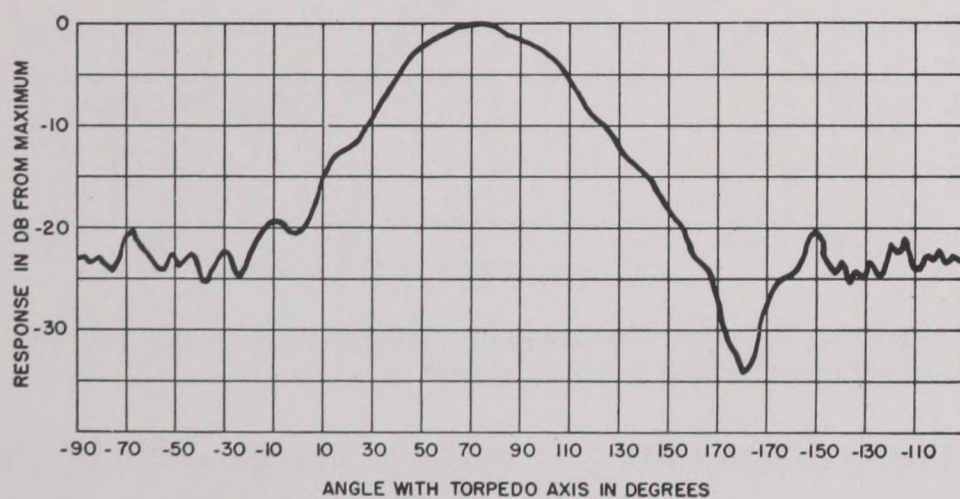


FIGURE 3. Directional response pattern of a crystal hydrophone, of the type used in the ExF42 mine, placed in a hemispherical nose.

hydrophone placed in the hemispherical nose of the torpedo. In this case it was 70 degrees off the axis. The response at 180 degrees, or straight back, is possibly 32 db below the maximum or some 5 db better than when mounted in the side position.

HUSL has made an important series of measure-

ments of the response to noise sources of hydrophones mounted in the head of a Mark 18 torpedo. The head was suspended under water and the sound source was similarly immersed a short distance away. The significant conclusion is that the discrimination is a function not only of the hydrophone and its immediate mounting but also of the nature of the shell in which it is mounted. This merely indicates the complication of the problem and shows that a simple calculation of the directional pattern is not adequate for describing the discrimination of the hydrophones against cavitation noise.

The assumption that the cavitation noise can be regarded as located in the water outside the torpedo is probably also inadequate. There is certainly an absorption of sound by the afterbody and possibly some of the sound is produced in contact with the propellers or other parts of the torpedo.

In particular it may be that some of the noise associated with the reversing gears is really cavitation noise. The water in the gears is certainly subject to variations in pressure that might well produce cavitation. This cavitation is in intimate contact with the gears and the noise may well be transmitted through the gears themselves. Isolation of the gears would then be an effective way of shielding the hydrophones from this part of the cavitation noise as well as from what might be more conventionally called machinery noise.

## 6.3 DISCRIMINATION AGAINST MACHINERY NOISE

Machinery noise is produced in direct metallic contact with the shell and is transmitted both through the shell and the water to the hydrophones. Apparently the exact process is a complicated interaction between the water and the shell that can be only partly described by saying that some energy is radiated into the water by the afterbody shell and that the energy is then absorbed from the water by the hydrophone. Nevertheless this partial description indicates why an isolation of the hydrophone from the shell is only partly effective. The discrimination seems to be improved by breaking the shell at one or more points, and also by a layer of absorbing material on the inside of the shell.



## Chapter 7

# TOTAL TORPEDO NOISE

THE PREVIOUS chapters have described the various sources of self noise in a torpedo and have indicated the nature of the evidence for the existence of cavitation noise and machinery noise that can be separated from each other to some extent by measuring the noise at various depths of submergence. A complete study of the noise of any one torpedo would involve running it at a variety of depths and speeds. From the curves of noise level as a function of depth for a given speed the curve of cavitation noise could be determined, and from a curve of noise as a function of speed for a constant cavitation coefficient, the machinery noise as a function of speed could be determined. By doing the same thing with different hydrophones, and different hydrophone positions, at least the relative values of the hydrophone discrimination could be determined.

Such a complete series of measurements is not available for any torpedo. The noise measurements that have been made have been carried out under the press of wartime conditions and the necessity of providing quick and rough information for the construction of usable weapons. These measurements do, however, provide some crude indications of the values of the various quantities. By using a liberal quantity of skepticism regarding the accuracy of the measurements and a certain amount of imagination, it is possible to build up curves that illustrate many of the trends shown in the observations.

With this object in mind, in this chapter, a series of assumptions will be made on the basis of which a group of theoretical curves can be plotted. These curves will not agree in any great detail with the observations, but they will illustrate the types of curves that may be met and the ways in which the different noise sources make themselves apparent.

### 7.1 ASSUMPTIONS

#### 7.1.1 Water Background Noise

In general there is a small background noise due to sources outside the torpedo. This is roughly isotropic and its full value will be measured by a non-directional hydrophone. In the neighborhood of 25 kc it will be assumed that the level of this noise is -54 dbs with one dyne per sq cm as the reference level.

#### 7.1.2

### Cavitation Noise

It will be assumed that for normal torpedoes the curve of cavitation noise level as a function of cavitation parameter is that given in Figure 1. The de-

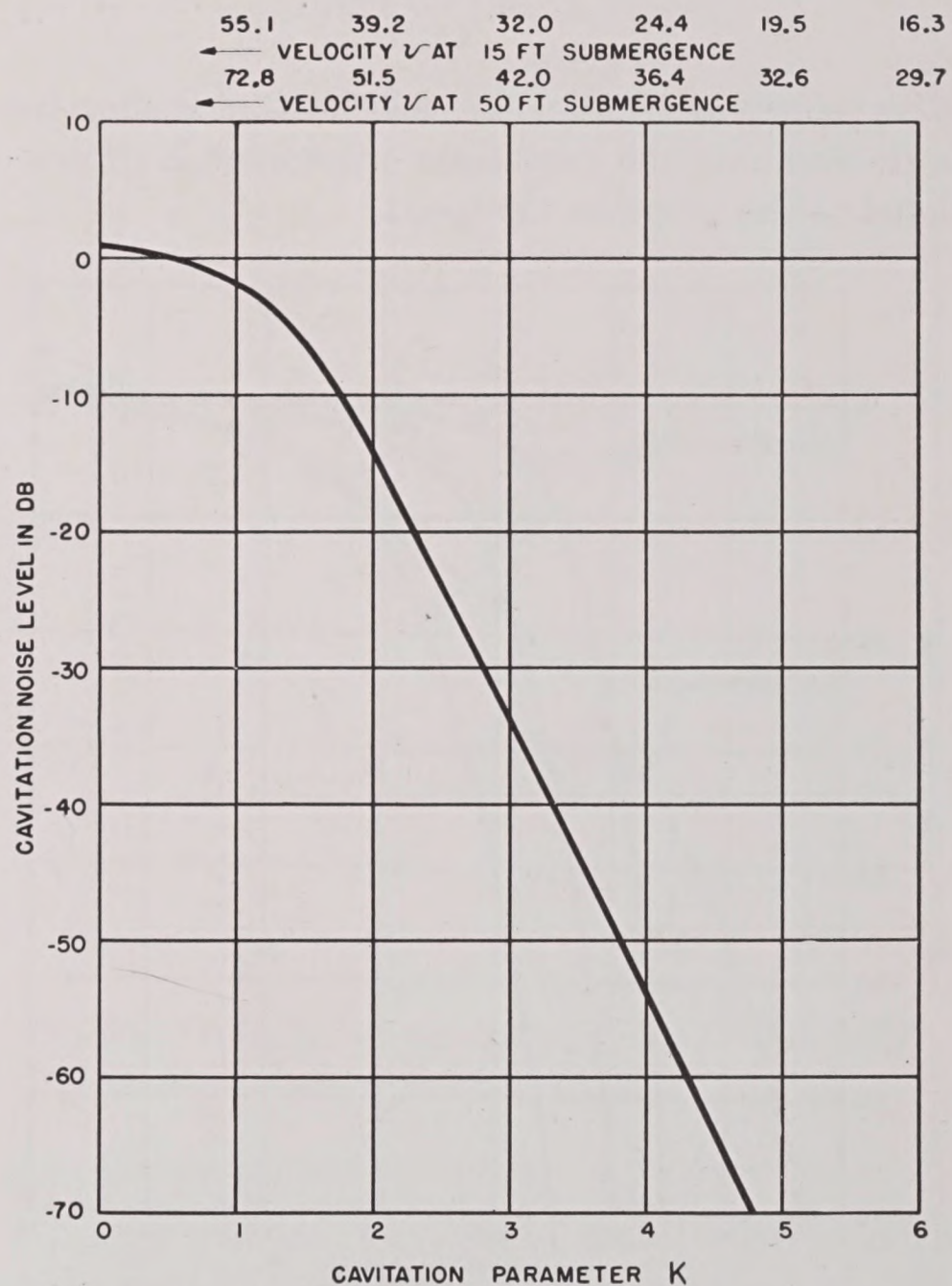


FIGURE 1. Assumed form of cavitation noise as a function of the cavitation parameter  $K$ .

tailed form of this curve is not very significant. The principal feature is that it rises rapidly as the cavitation parameter decreases, and then levels off.

The curve as drawn in Figure 1 is based on the use of the forward speed of the torpedo in evaluating the cavitation parameter. If the cavitation were on the nose, or on some fixed part of the torpedo, such as a fin or a rudder, this would unquestionably be the correct velocity. Since, however, the cavitation probably develops on the propellers, the forward velocity is the only correct one to use when torpedoes with approximately similar propellers are being compared. Apparently most normal torpedoes are sufficiently similar so that the forward speed is proportional to the propeller tip speed in most cases. How-



ever, when single propellers are used, or propellers of radically different pitch, it is necessary to use a corrected parameter  $K'$ . If  $v_p^\circ$  is the propeller tip speed of the normal torpedo at the running speed in question, and if  $v_p'$  is the tip speed of the modified type of propeller, then the value of the cavitation parameter to be used with the modified propeller is

$$K' = \left( \frac{v_p^\circ}{v_p'} \right)^2 2K.$$

With this understanding the velocity that is effective in determining the cavitation parameter is proportional to the propeller tip speed.

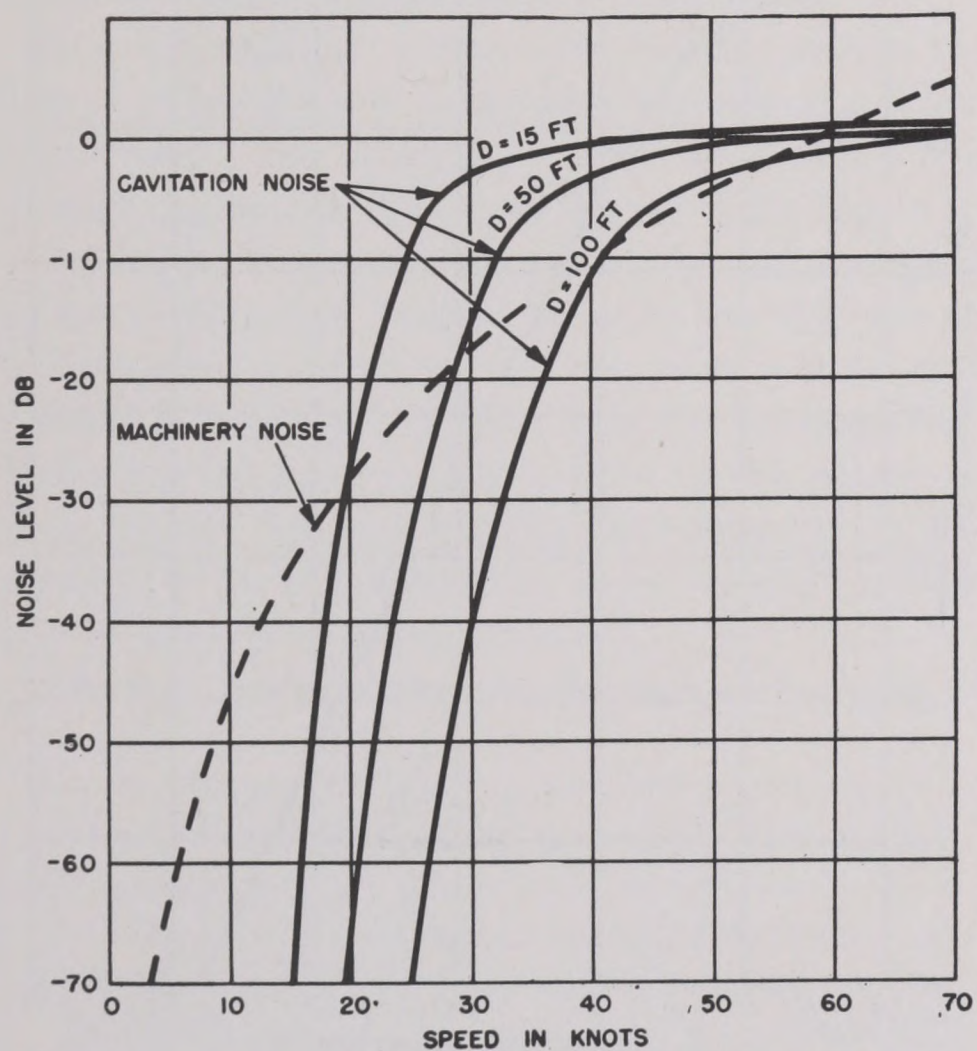


FIGURE 2. Assumed cavitation noise level as a function of speed for three depths and the assumed machinery noise level.

### 7.1.3 Machinery Noise

It will be assumed that the machinery noise is proportional to the sixth power of the torpedo speed. This seems a rather surprising law but it agrees with the general trend of the observations moderately well.

A British report<sup>14</sup> describes measurements of torpedo noise in which the sound intensity was proportional to the eighth power of the speed. However, since the measured noise probably included cavitation noise, the observation is not definitive.

It might seem reasonable that the noise would vary as the third power of the speed, since the power

of the engine follows this law and it might be expected that a constant fraction of the power would go into noise. Nevertheless it appears that the  $v^6$  law agrees with the overall picture of the observations as well as anything else, and it will be used in the following curves. Let it be emphasized again, however, that this particular form of law has no direct experimental basis.

### 7.1.4 Hydrophone Discrimination

Each hydrophone, hydrophone position or hydrophone isolation will be represented by a certain sensitivity to, or discrimination against, cavitation noise on the one hand and machinery noise on the other. In addition there will be a certain discrimination against background noise which is given by the directivity index of the hydrophone. This latter, however, is of negligible importance in most cases.

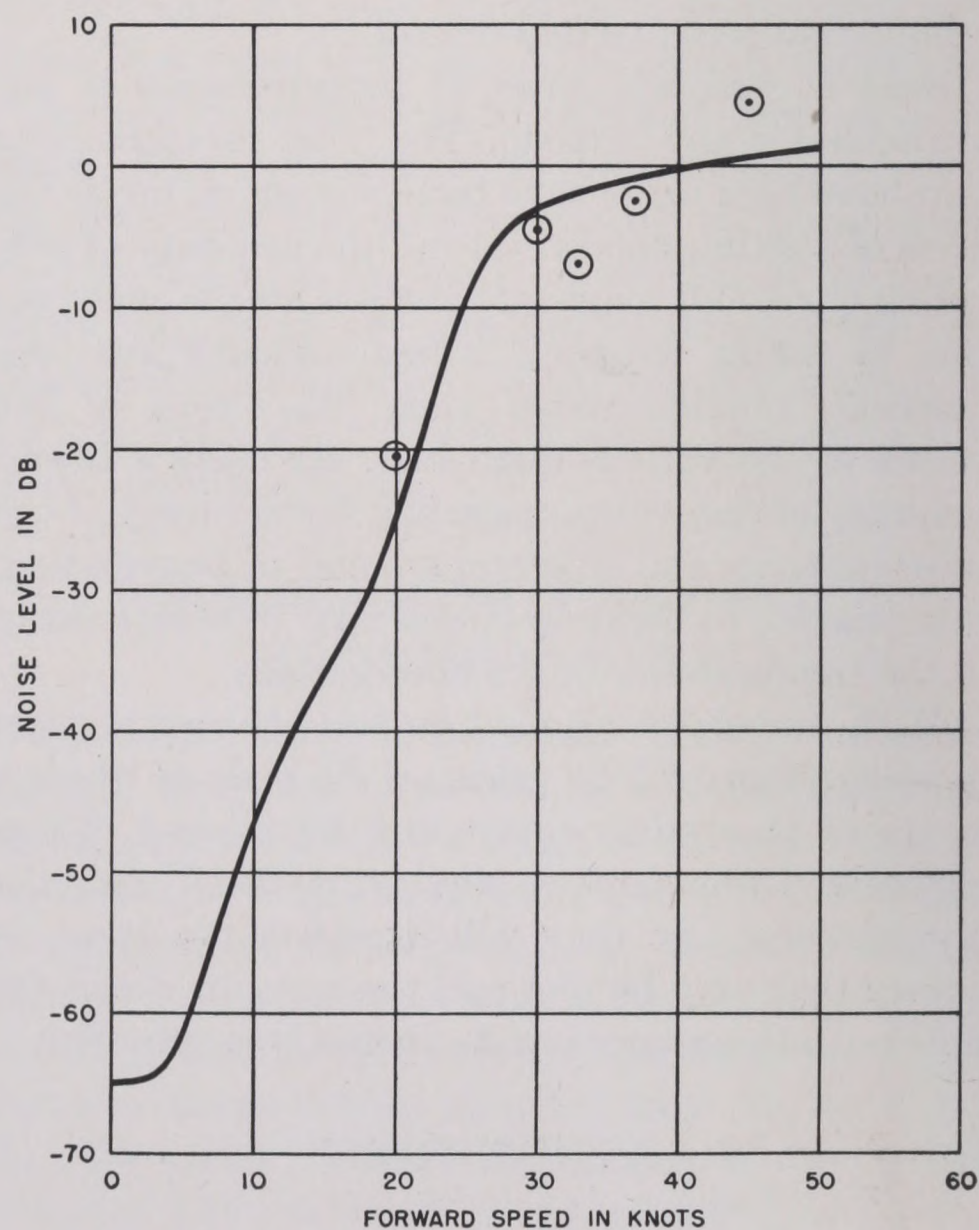


FIGURE 3. Total noise at 15-ft depth on the basis of idealized assumptions. Points are representative of the observations shown in Figure 1 (Chapter 1) and are the same as those in Figure 2 (Chapter 1).

### EXTERNALLY MEASURED NOISE

As was indicated in Chapter 3 the noise from most standard torpedoes can be represented as a function of speed by a single curve. The indications seem to



be that between 20 and 30 knots cavitation noise and machinery noise are near to the same order of magnitude but that cavitation noise is definitely predominant at 30 knots. For speeds as high as 45

ing way in which the noise may depend on depth at a constant speed. Characteristic of the latter curves is the drop with increasing depth to the machinery noise limit beyond which the noise does not decrease.

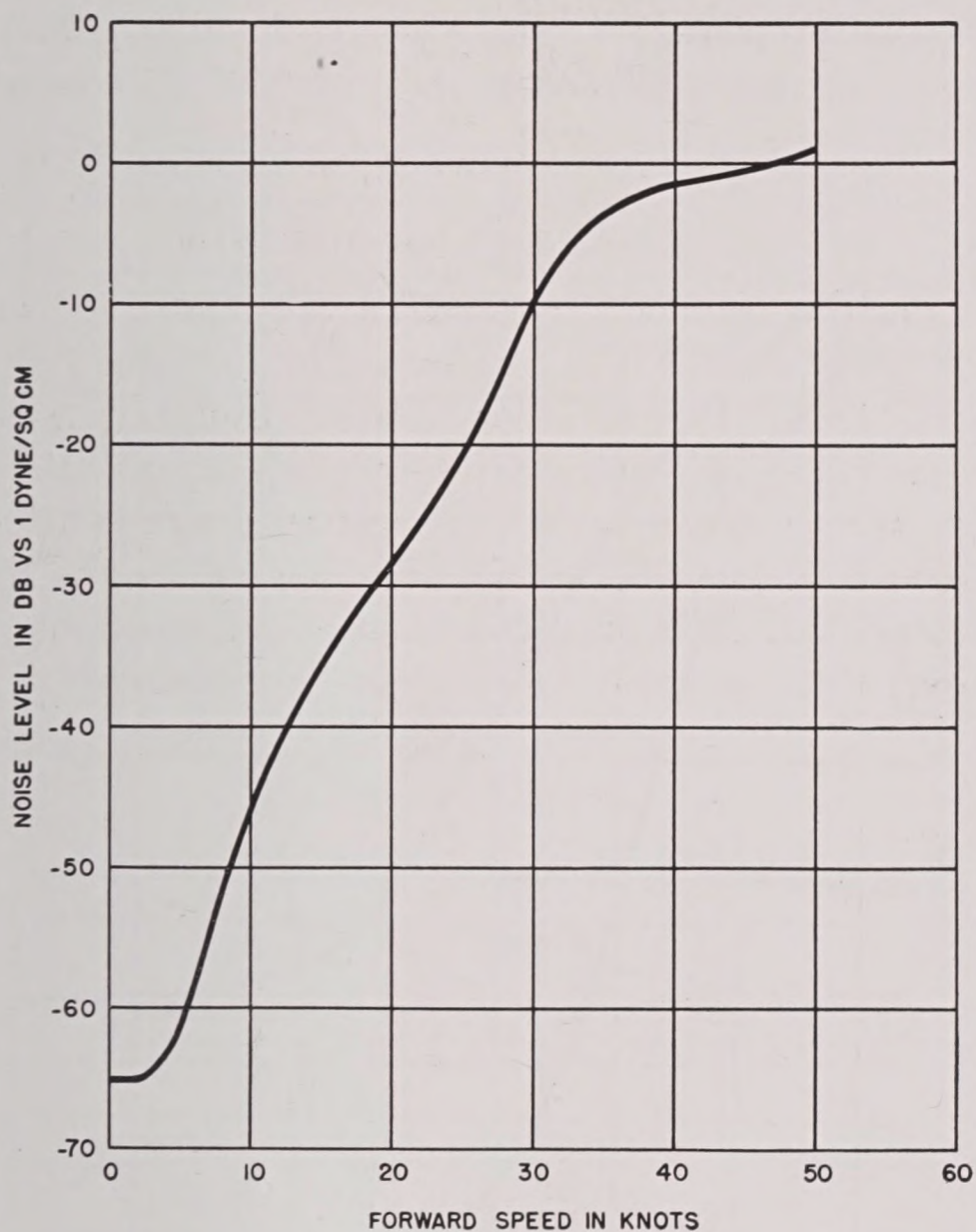


FIGURE 4. Total external torpedo noise at 40-ft depth on the basis of idealized assumptions.

knots the machinery noise seems to have increased again until it is in the lead. We may then construct curves on the following basis.

1. Background noise level is  $-54$  db.
2. Cavitation noise level is given in Figure 1.
3. Machinery noise level is given by  $L(v) = 60 \log v - 120$ , where  $v$  is the speed in feet per second.

Figure 2 shows the cavitation level and the machinery level plotted separately and Figure 3 shows the sum. These figures show the way in which first one source of noise and then the other can be dominant. The five points indicated are the points from Figure 2 in Chapter 3 and indicate that in a very rough way the composite curve of noise as plotted is in agreement with the observations.

Figures 4 and 5 show a way in which the noise-speed curves may depend upon the depth at which they are taken, and Figure 6 shows the correspond-

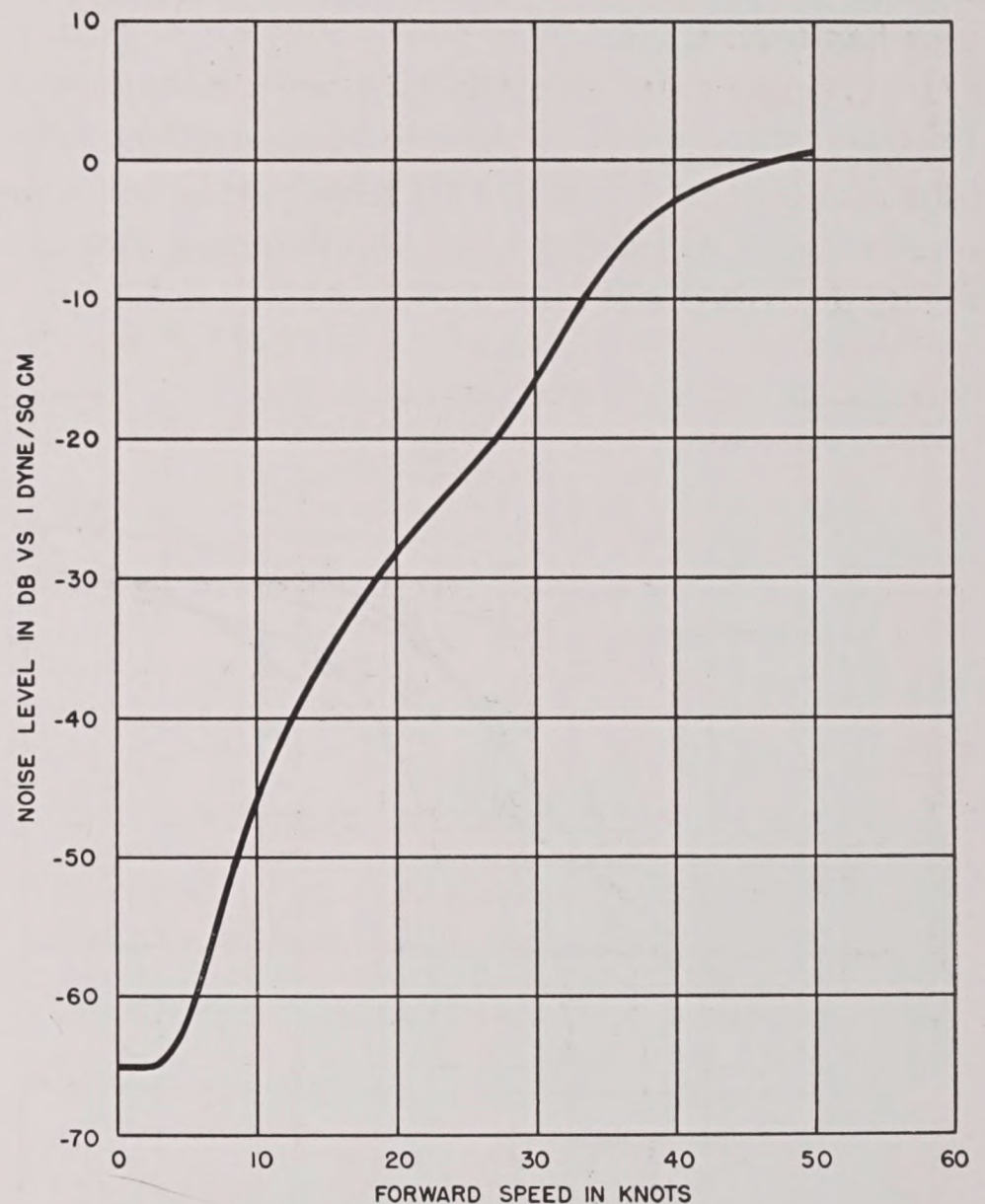


FIGURE 5. Total external torpedo noise at 60-ft depth on the basis of idealized assumptions.

#### SELF-NOISE MEASUREMENTS

During the past two years the Harvard Underwater Sound Laboratory [HUSL] and the Bell Telephone Laboratories [BTL] have made extensive

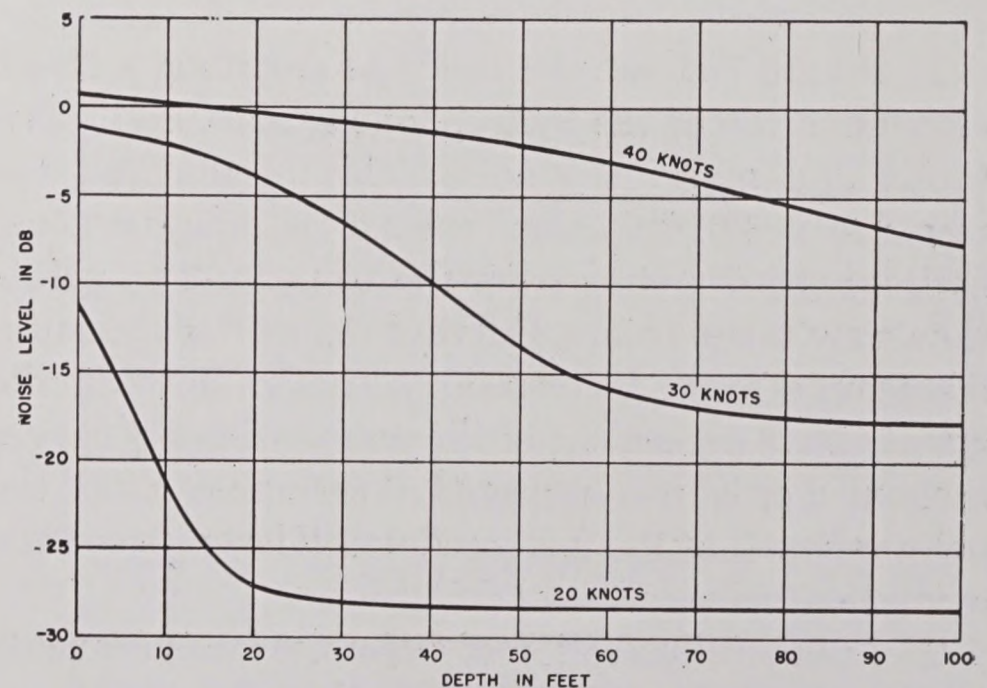


FIGURE 6. Total external torpedo noise as a function of depth for three different speeds, based on idealized assumptions.



measurements of self noise in various torpedoes. Neither of them has made as complete a set as might be desired but it is possible to use their observations for crude estimates of the quantities involved and as a rough justification for the description of this noise that has been used.

In trying to understand self-noise measurements the discrimination of the hydrophones must be taken into account, and it is in this respect that self-noise observations will differ from the external measurements described above.

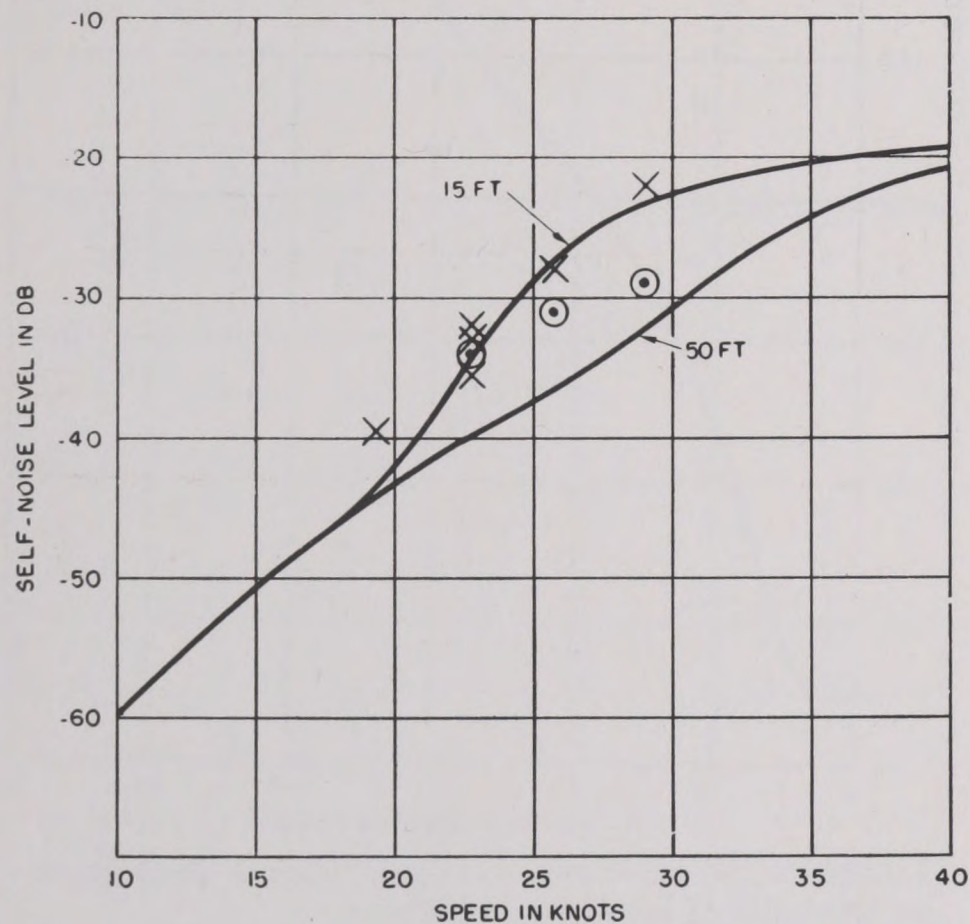


FIGURE 7. Self-noise level at 25 kc for two different depths. The hydrophone is assumed to have a discrimination of 20 db against cavitation noise and 15 db against the machinery noise. The points are taken from measurements by the Harvard Underwater Sound Laboratory.<sup>15</sup>

1. Figure 7 shows the result of assuming a 20-db discrimination of the hydrophone against both cavitation and machinery noise. This means that the response is 20 db below that of a nondirectional hydrophone 6 meters from the torpedo. The points shown are taken from a Harvard report<sup>15</sup> of measurements on a Mark 18 torpedo. Although nothing like quantitative agreement of the points with the curves is claimed or is to be expected, it seems clear that the points show that the increased depth has reduced the cavitation noise.

2. Another illustration of self-noise measurements is given in Figure 8. This shows the noise as a function of depth for two different speeds. Since the torpedo was a Mark 18 driven by a single propeller, it

was necessary to make use of a  $K' = 0.455 K$  instead of the usual  $K$ . In plotting the theoretical curves it is assumed that the hydrophone discrimination against the cavitation was 30 db and against the machinery noise 18 db. The points are taken from one of the Harvard reports.<sup>16</sup>

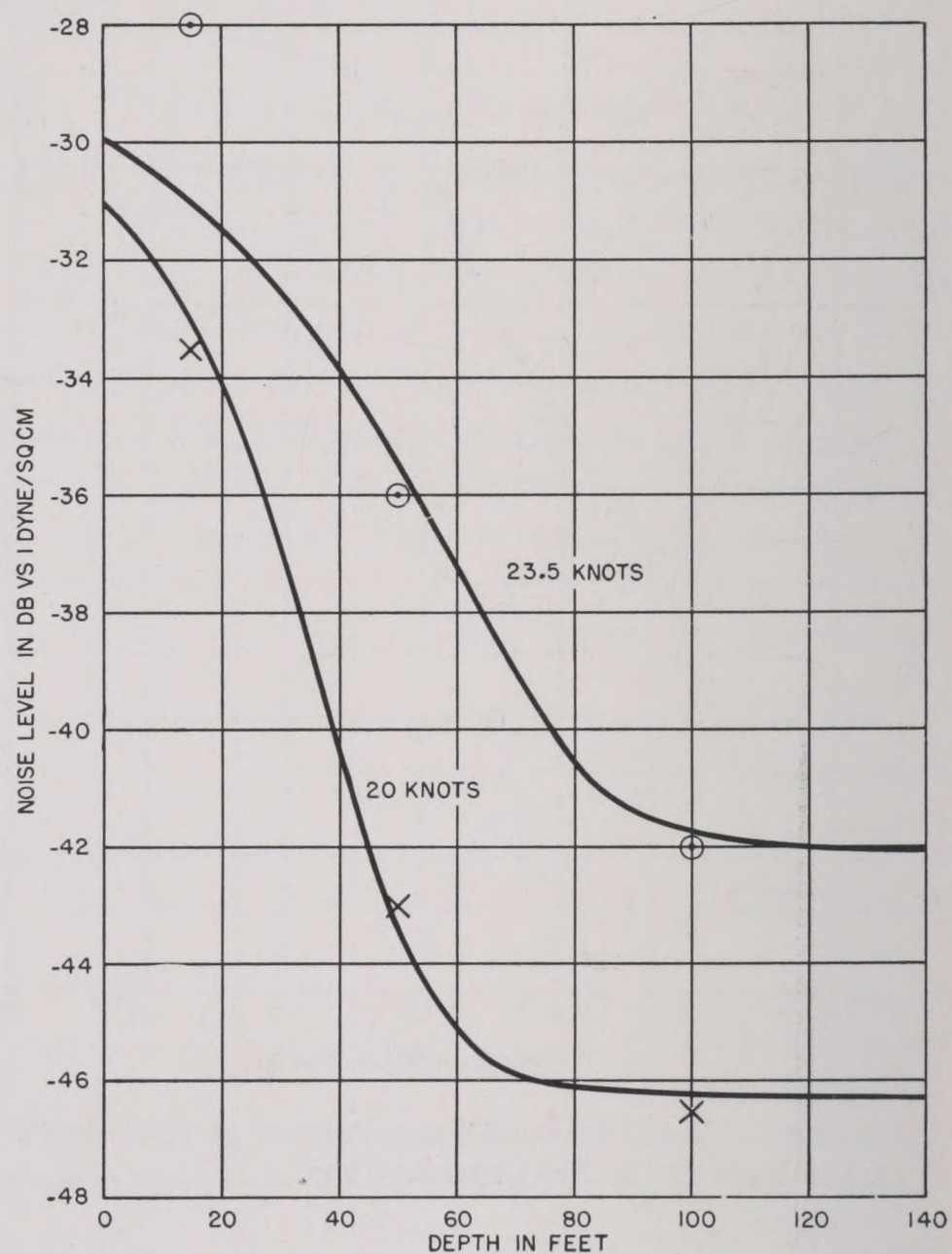


FIGURE 8. Self-noise level at 25 kc for two different speeds. The cavitation is described in terms of a parameter  $K' = 0.455K$ , and the hydrophone discrimination was assumed to be 30 db against cavitation noise and 18 db against machinery noise. The points represent measurements by the Harvard Underwater Sound Laboratory.<sup>16</sup>

3. Figure 9 shows that it is possible to understand a curious phenomenon noted in some of the measurements in which nose hydrophones were compared with body hydrophones. The Harvard observations<sup>17</sup> seemed to show that in the study of the Mark 18 with a single propeller the curves of noise level as a function of depth for the body hydrophone seemed to cross the corresponding curve for the nose hydrophones. Although it is important not to stress too much the accuracy of a few observations under difficult conditions, it is of interest to note that this effect can be produced if the different hydrophones are



assigned the proper discrimination. The fact that the change in hydrophone position affects the two types of discrimination differently makes possible such phenomena, and it is clear that it is quite reasonable to expect such differences.

4. Figure 10 shows a pair of curves of self-noise level as a function of depth corresponding to speeds

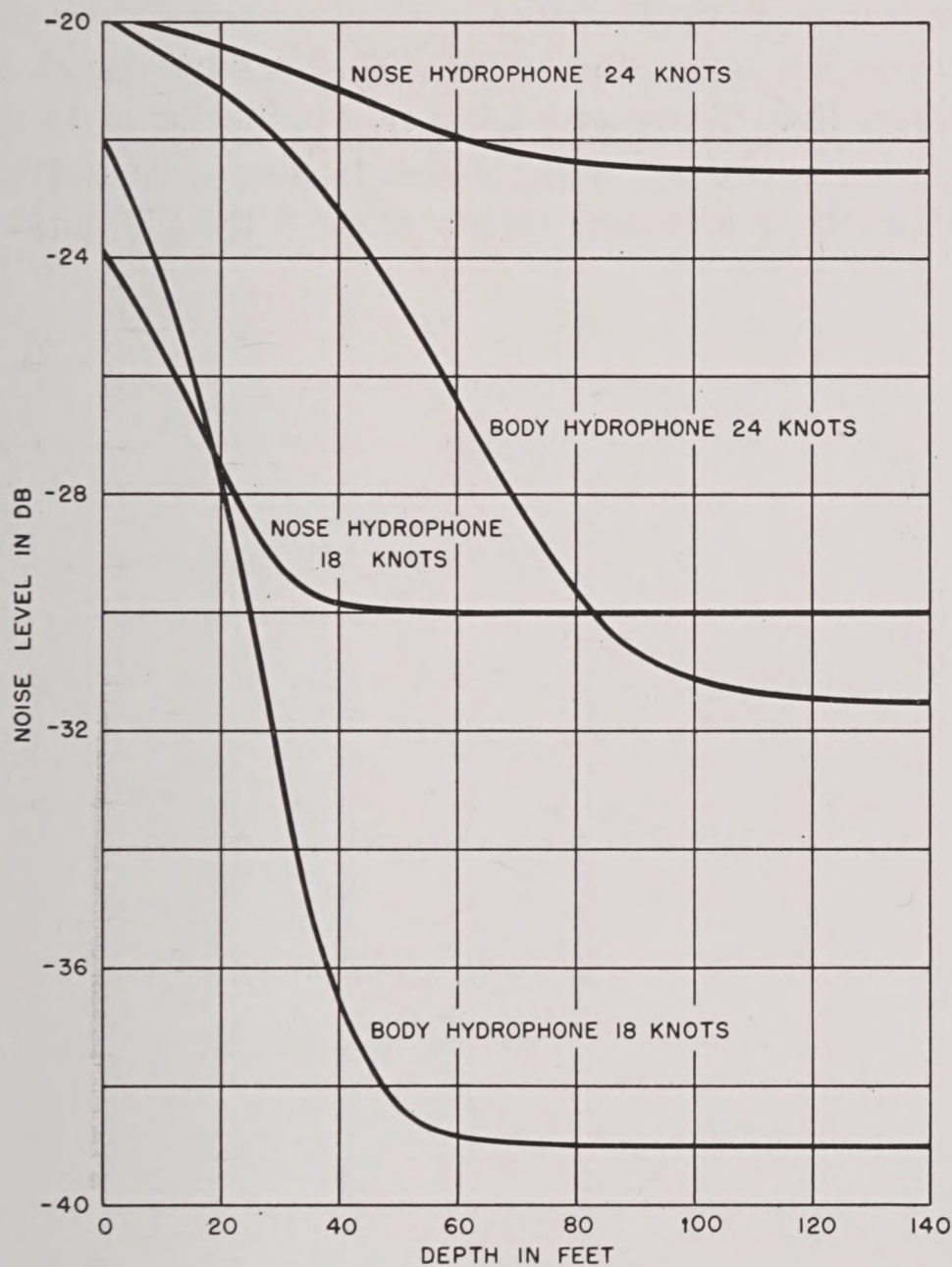


FIGURE 9. Self-noise level at 25 kc for two different speeds and two different hydrophones. In addition to the idealized assumptions as to the magnitude of the noise produced, it is assumed that the nose hydrophones discriminate against cavitation by 23 db and against machinery noise by -1 db, while the body hydrophones discriminate against the cavitation noise by 20 db and against the machinery noise by 8 db. The cavitation parameter  $K' = 0.455K$  is used.

of 33 knots and 28 knots respectively. These have been drawn on the assumption that the hydrophones discriminate against the cavitation noise to the extent of 25 db and against the machinery noise to the extent of 20 db. Points are shown indicating results obtained by HUSL on the Mark 13 torpedo. The coincidence of the two points at the 50-ft depth is of course entirely contrary to the general trend of the curves which are approaching limiting values corresponding to the difference between the ma-

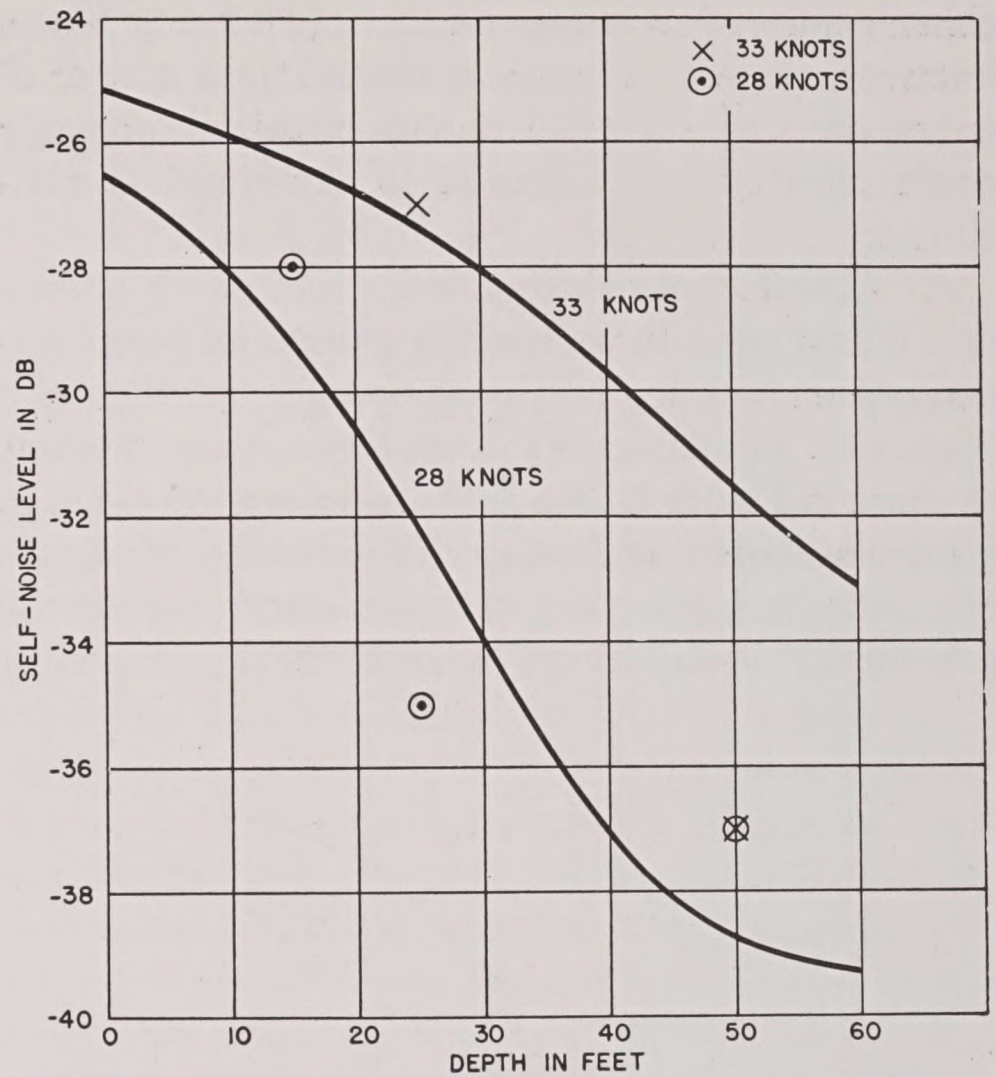


FIGURE 10. Self-noise level at 25 kc for two different speeds of the Mark 13 torpedo. The hydrophone appears to be such that a 25-db discrimination against cavitation noise is assumed in drawing the curves. The discrimination against the machinery noise is assumed to be 20 db. The points are taken from a report from the Harvard Underwater Sound Laboratory.<sup>18</sup>

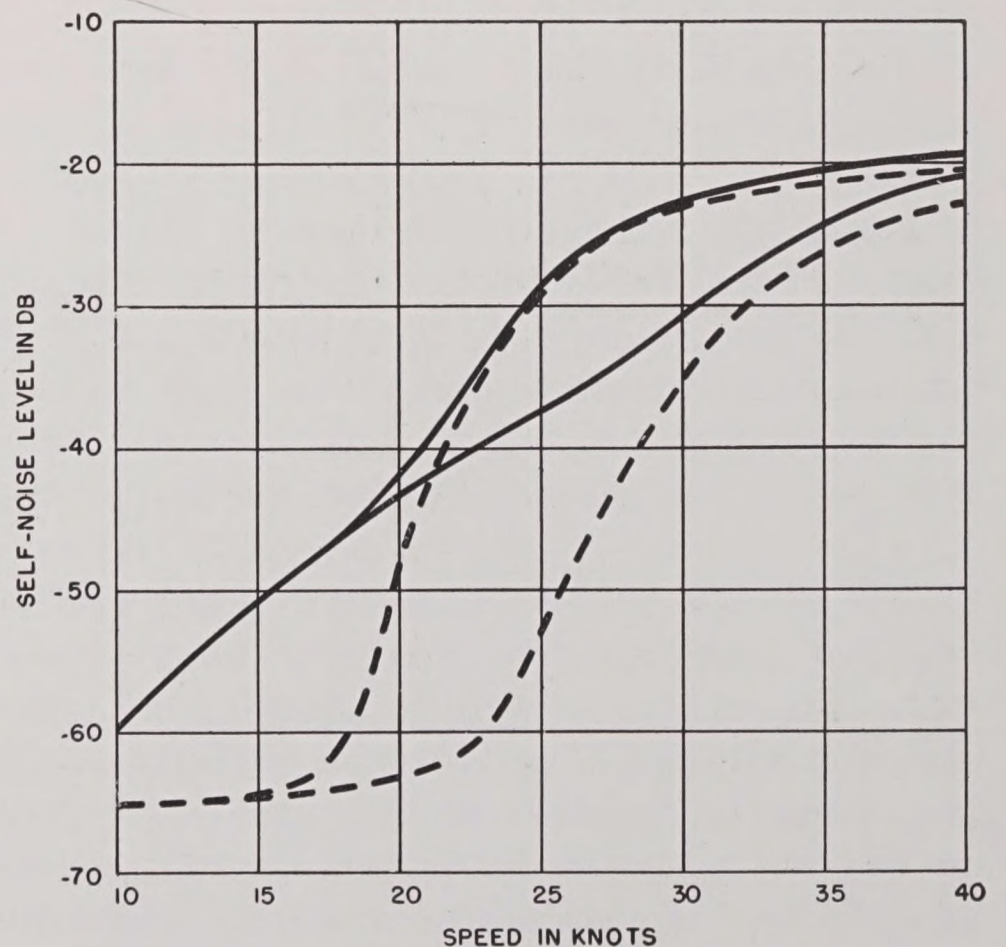


FIGURE 11. Self-noise level at depths of 15 and 50 ft as a function of speed. The solid curves correspond to a discrimination against cavitation noise of 20 db and against machinery noise of 15 db. The dotted curves correspond to the same discrimination of 20 db against cavitation noise, but a discrimination of 30 db against machinery noise.



chinery noise of 28 knots and that of 33 knots. Since, however, these curves are separated by a matter of only 6 db, a considerable amount of this discrepancy could possibly be attributed to experimental difficulties.

5. The effect of reducing or discriminating against machinery noise is very much dependent upon torpedo speed and depth. This is brought out clearly in Figure 11. In this figure the solid curves are the same as those in Figure 7. The dotted curves correspond to a discrimination against cavitation noise of 20 db, but a discrimination against machinery noise or else a reduction in machinery noise of 30 db. It is clear

from these curves that at 15 knots the machinery noise, with only 15-db discrimination against it, was the principal contribution to the self noise. At 35 knots, the cavitation is much more prominent, although the machinery noise is clearly more significant at 50 ft than at 15 ft. This kind of curve illustrates the way in which a real reduction in machinery noise might be completely masked if the measurements were made under such conditions that the cavitation noise dominates. On the other hand, it shows that the observed fact of a reduction of 15 db in the machinery noise, which is clearly evident at 15 knots, is no longer nearly so striking at 30 knots.



## Chapter 8

# TRANSFORMATION OF ACOUSTIC SIGNAL INTO A DIRECT-CURRENT VOLTAGE

TO MAKE USE of the acoustic signal for control of the torpedo, a circuit must be devised that transforms the hydrophone response into a suitable signal for actuating the rudder. There are many ways of doing this, but for illustrating the principles involved the schematic diagram of Figure 1 may be regarded

### 8.1 DESCRIPTION OF A SIMPLE CIRCUIT

$H_p$  and  $H_s$  are respectively the port and starboard hydrophones. The signal from each of these first goes through an amplifier and then to a detector, which may be considered to be a "square law" detector. It is essential that both amplifiers have the same gain, and the maintenance of this equality of gain is one of the principal problems in designing a suitable circuit. Nevertheless, this difficulty will be ignored for the present, and it will be assumed that the gains are equal. This problem will be mentioned again later. Under this assumption, the d-c outputs of the detectors will be proportional to the intensities of the responses of the corresponding hydrophones.

The two d-c signals, of the same sign, are then put into the condensers  $C_p$  and  $C_s$  and the resistances  $R_p$  and  $R_s$ . The potential  $V_d$  across the resistances is then proportional to the difference between the responses of the two hydrophones. It is positive when  $H_s$  gives the stronger response and negative when  $H_p$  is affected more strongly. The condensers and resistances are adjusted to give the desired time constant to the system. When they are large, the signal is averaged over a correspondingly long period of time and the system is not much affected by sudden sharp bursts of noise. On the other hand, the time constant must not be long compared with the dynamic time constants of the torpedo body, or the system will not respond quickly enough to steer correctly.

The voltage  $V_d$  is then combined with the voltage from the potentiometer  $P_r$  and applied to a polarized relay. The resistance of this relay must be large, since it is parallel with  $R_p$  and  $R_s$  and affects the time constant of the circuit. If the resultant voltage  $V_r$  has one sign, the arm is pulled to contact  $a$ ; if it has the other sign, the arm moves to contact  $b$ . There may also be a neutral position taken if  $|V_r| < V_{r0}$ . When the relay makes one contact or the other, the battery  $B_m$  drives the motor in one direction or the other. This turns the rudder and, since the rudder is mechanically connected to the potentiometer arm, the

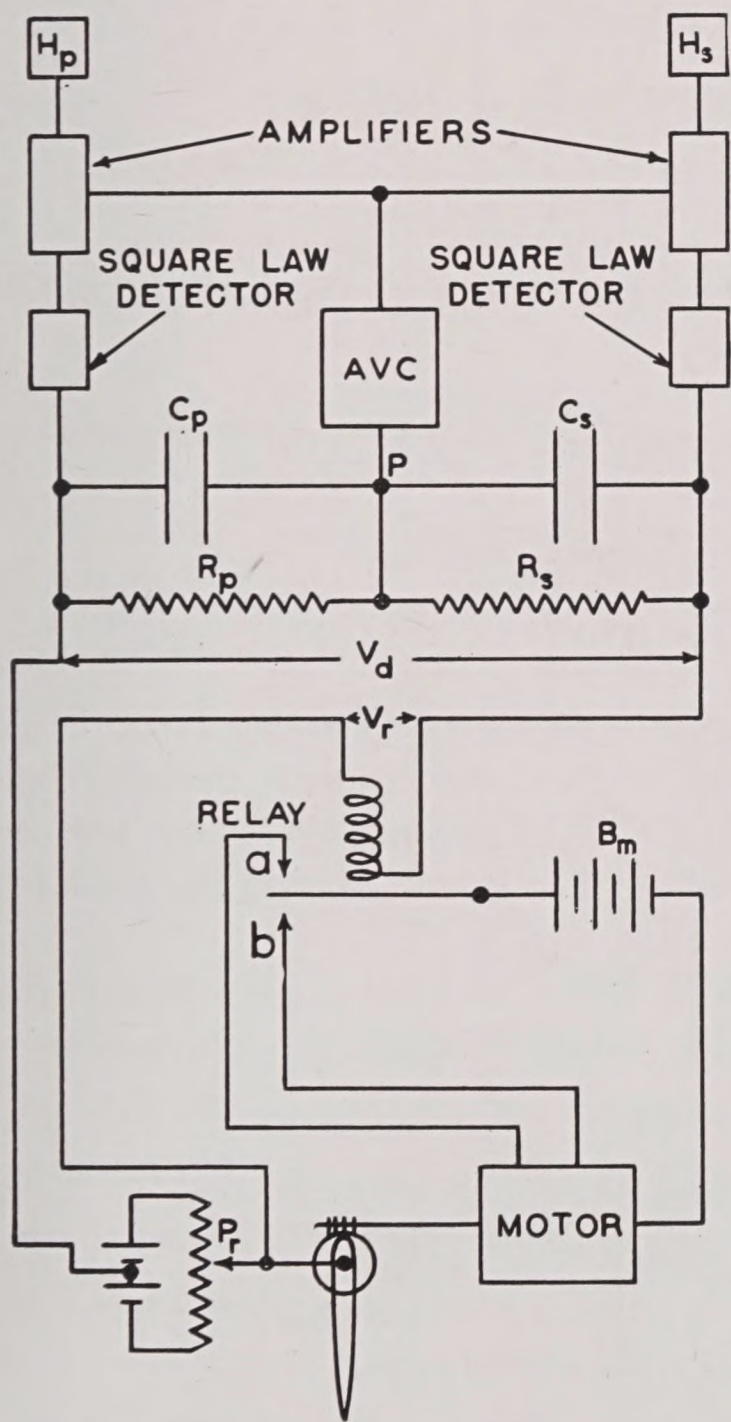


FIGURE 1. Schematic diagram of a simple circuit for acoustic listening homing.

as typical. This circuit is drawn for steering in the horizontal plane and it is intended to operate so that the rudder position is a function of the direction from which the acoustic signal is coming. When this direction is near the axis of the torpedo, the rudder deflection is intended to be at least roughly proportional to the angle from which the signal comes.



motion of the rudder changes the potential applied from the potentiometer  $P_r$ . If the relay has a neutral position, the motor will stop when  $V_r = (V_d - V_p)$  is near zero. This is when the potentiometer voltage is equal and opposite to  $V_d$ . The rudder deflection is then proportional to the voltage  $V_d$ , since it is proportional to  $V_p$ . This is of course only true until the arm gets to the end of the potentiometer or the rudder reaches its stops. If the relay has no neutral position, the rudder will oscillate about the equilibrium position with a frequency that depends on the constants of the motor and the relay, and it will be the equilibrium position that is proportional to  $V_d$ .

It is clear that the relay will not operate on an infinitesimal voltage, and furthermore that the voltage corresponding to full rudder deflection is a finite voltage. On the other hand, the acoustic signal varies through wide limits as the torpedo approaches its target. For this reason, some means are necessary to change the gain of the amplifiers in accordance with the strength of the signal. One method of doing this is to use an automatic volume control governed by the potential of the point  $P$ . This has a potential proportional to the average intensity of the responses of the two hydrophones. It is amplified as necessary and applied to the grids of the amplifiers in such a way that the gain is reduced when the average response increases. It may be designed so that the gain  $G$  has its maximum value  $G_0$  until the mean response corresponds to some value  $P_0$ , after which the gain is inversely proportional to the potential  $P$ .

Each hydrophone has a response that is a function of the direction from which the signal comes. Let this be  $R_p(\theta)$  for the port hydrophone and  $R_s(\theta)$  for the starboard hydrophone. Let  $\theta$  be the angle that the direction of the signal makes with the axis of the torpedo. Consider  $\theta$  positive when on the starboard side and negative on the port side.  $R_p(\theta)$  then has its maximum for a negative value of  $\theta$  and  $R_s(\theta)$  has its maximum for a positive value of  $\theta$ . These responses  $R_p$  and  $R_s$  are expressed in db with reference to 1 volt rms output for a sound wave of 1 dyne per sq cm rms sound pressure. Correspondingly, let  $R_p^\circ$  and  $R_s^\circ$  be the maximum responses of the corresponding hydrophones. If the hydrophones and their corresponding amplifiers are perfectly balanced and matched,  $R_s^\circ = R_p^\circ$  and  $R_p(\theta) = R_s(-\theta)$ . However, the matching is not perfect, and especially in setting up a manufacturing procedure some lack of balance must be expected. Since the amount of the unbalance is one factor in limiting the performance, let  $R_s^\circ = R^\circ + \delta$

and  $R_p^\circ = R^\circ - \delta$ . In order not to complicate the discussion here too much, it will be assumed, however, that the two hydrophone patterns are similar, so that

$$R_p(\theta) + \delta = R_s(-\theta) - \delta.$$

Let  $L_n$  be the effective level of the self noise plus the background noise at the frequency passed by the hydrophones and amplifiers. As indicated previously this means that the self noise produces a response in the hydrophones equivalent to that produced by a plane wave of level  $L_n$  incident from the direction of maximum response. Then in the absence of a signal, the voltages will be

$$V_p = G10^{(L_n + R_p^\circ)/10}$$

and

$$V_s = G10^{(L_n + R_s^\circ)/10}. \quad (1)$$

Under these circumstances, the potential of the point  $P$  will be

$$P = \frac{G}{2} 10^{(L_n + R^\circ)/10} (10^{\delta/10} + 10^{-\delta/10}), \quad (2)$$

and the voltage  $V_d$  will be

$$V_d = G10^{(L_n + R^\circ)/10} (10^{\delta/10} - 10^{-\delta/10}). \quad (3)$$

This  $V_d$  will be zero only if the two hydrophones with their amplifiers and detectors are perfectly balanced, i.e., when  $\delta = 0$ . In general, this is not the case, and a slight differential  $V_d$  will exist in the absence of any signal at all.

If now a signal of level  $L_s$  is incident from the angle  $\theta$ , the responses of the two hydrophones will be

$$\begin{aligned} V_s &= G \{ 10^{(L_n + R^\circ + \delta)/10} + 10^{(L_s + R_s(\theta))/10} \} \\ V_p &= G \{ 10^{(L_n + R^\circ - \delta)/10} + 10^{(L_s + R_p(\theta))/10} \} \end{aligned} \quad (4)$$

$$V_s = G10^{(L_s + R^\circ)/10} \{ 10^{(L_n - L_s + \delta)/10} + 10^{(R_s(\theta) - R_s^\circ + \delta)/10} \} \quad (5)$$

$$V_p = G10^{(L_s + R^\circ)/10} \{ 10^{(L_n - L_s - \delta)/10} + 10^{(R_p(\theta) - R_p^\circ - \delta)/10} \}$$

$$V_d = G10^{(L_s + R^\circ)/10} \{ 10^{(L_n - L_s)/10} (10^{\delta/10} - 10^{-\delta/10}) + 10^{(R_s(\theta) - R_s^\circ + \delta)/10} - 10^{(R_p(\theta) - R_p^\circ - \delta)/10} \} \quad (6)$$

$$\begin{aligned} P &= \frac{G}{2} 10^{(L_s + R^\circ)/10} \{ 10^{(L_n - L_s)/10} (10^{\delta/10} + 10^{-\delta/10}) \\ &\quad + 10^{(R_s(\theta) - R_s^\circ + \delta)/10} + 10^{(R_p(\theta) - R_p^\circ - \delta)/10} \} \end{aligned} \quad (7)$$

The quantity  $P$  determines the gain of the amplifiers. For illustration, assume that the AVC is so built that  $P$  never exceeds the value 2 v. As long as



$2P/G \leq 4$ ,  $G = 1.00$ , but for larger values  $P$  is held constant at 2.00.

The question of the value of  $\delta$  is largely one of manufacturing reproducibility. For illustration, assume  $\delta = 1$ . This is an extreme value, since the experience on the ExF42 mine suggests that  $\delta \leq 0.2$  can be maintained by careful balancing of the system after the hydrophones are installed in the body and connected to the circuit. Nevertheless,

time constants of the circuits are not involved. Figure 2 shows the voltage  $V_d$  when the gain is so adjusted that the self noise gives a voltage of 1 volt when the hydrophone response is  $R^\circ$ . Since the hydrophones are expected to deviate from this by 1 db, the noise, in the absence of any signal, produces a response from the starboard hydrophone of 1.26 volts and from the port hydrophone of 0.79 volt. In the absence of any signal the steering voltage  $V_d$  is this

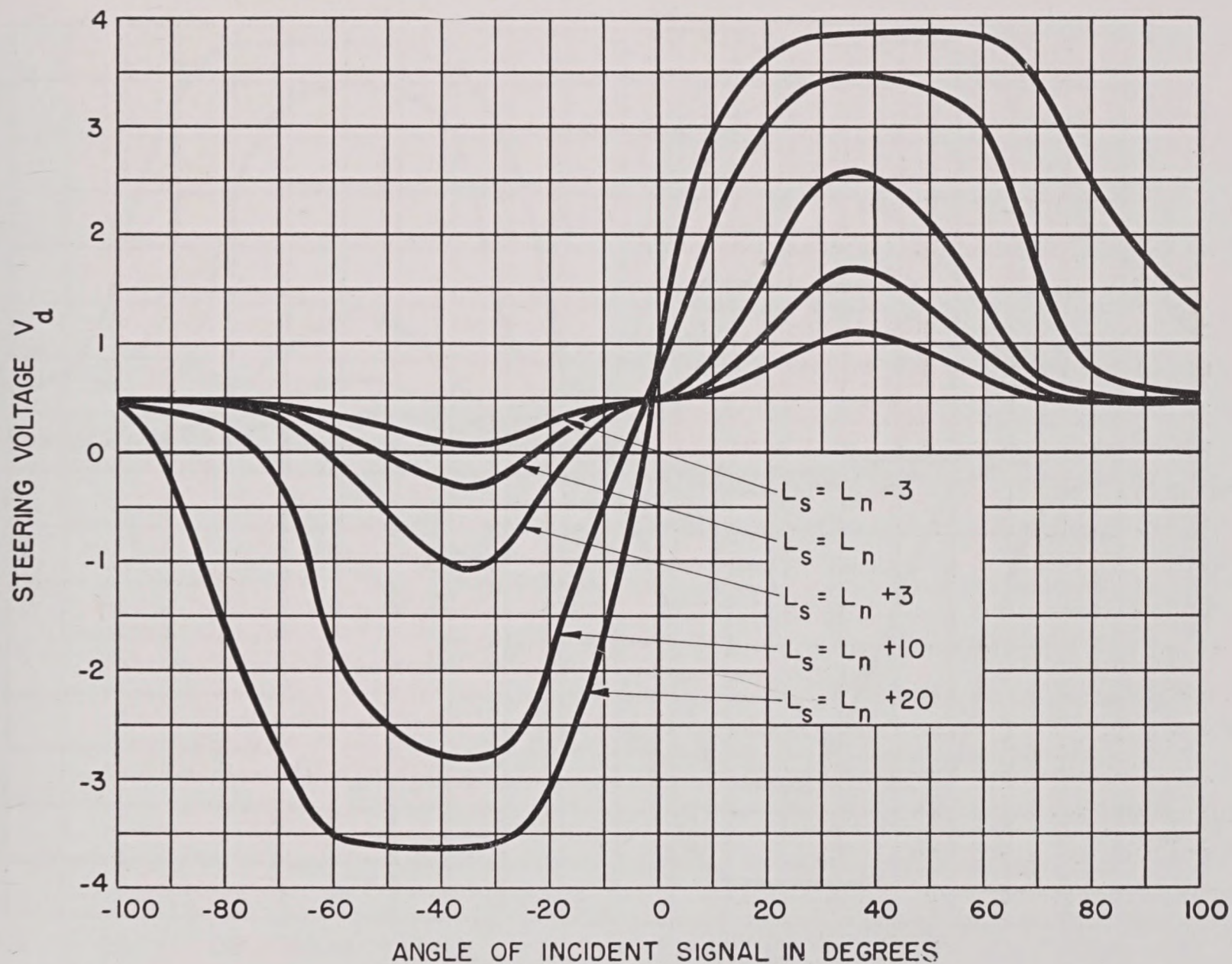


FIGURE 2. Illustration of the steering voltage  $V_d$  as a function of the angle  $\theta$  from which the signal comes for various values of signal strength. The gain is set so that the response of a hydrophone to the self noise gives a 1-v response, and the AVC is so designed that it does not come into play until the potential of the point  $P$  in Figure 1 reaches 2 v. Thereafter the potential of  $P$  is held down to 2 v.

$\delta = 1$  will be assumed in the curves to be drawn, since in this way the effect of the unbalance is emphasized and can be more easily seen.

The quantities  $R_s(\theta)$  and  $R_p(\theta)$  depend on the type of hydrophone used and the way it is mounted in the shell. For illustration, use the directional pattern shown in Figure 2 in Chapter 6.

Figures 2, 3, and 4 show the voltage  $V_d$  as a function of the direction  $\theta$  from which the signal comes. This assumes, of course, a static situation so that the

0.47 volt. If the signal is 3 db below the noise, the voltage  $V_d$  is always positive so there can be no steering control. Under these circumstances, the rudder will be always to the right and the torpedo will circle. Since, in all probability, the minimum value of  $V_d$  will not at all give maximum rudder, the path will not be a circle of constant minimum radius, but will change in curvature. Nevertheless, the torpedo will turn around and in this way search for a target. This search mechanism is of use in the ExF42 mine,

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but in a torpedo which is expected to start out on a gyro-controlled course some means must be adopted for steering on gyro until the signal is strong enough to give good steering. Such a device is generally called a "gate" and will be discussed later.

Other curves in Figure 2 show the voltage when the signal level is equal to and greater than the self noise. It is clear that the "stiffness" of the control, the volts per degree displacement from the desired course, is a function of the signal strength and, as will be shown

practical manufacture, may be in one direction or the other and it may be made the basis of a simple search procedure.

2. The unbalance of the hydrophones causes a zero steering voltage to correspond to angles other than zero. This angle becomes smaller, however, as the strength of the signal increases. As a consequence, the torpedo will tend to approach the target in a spiral.

3. The unbalance in the hydrophones, or in the

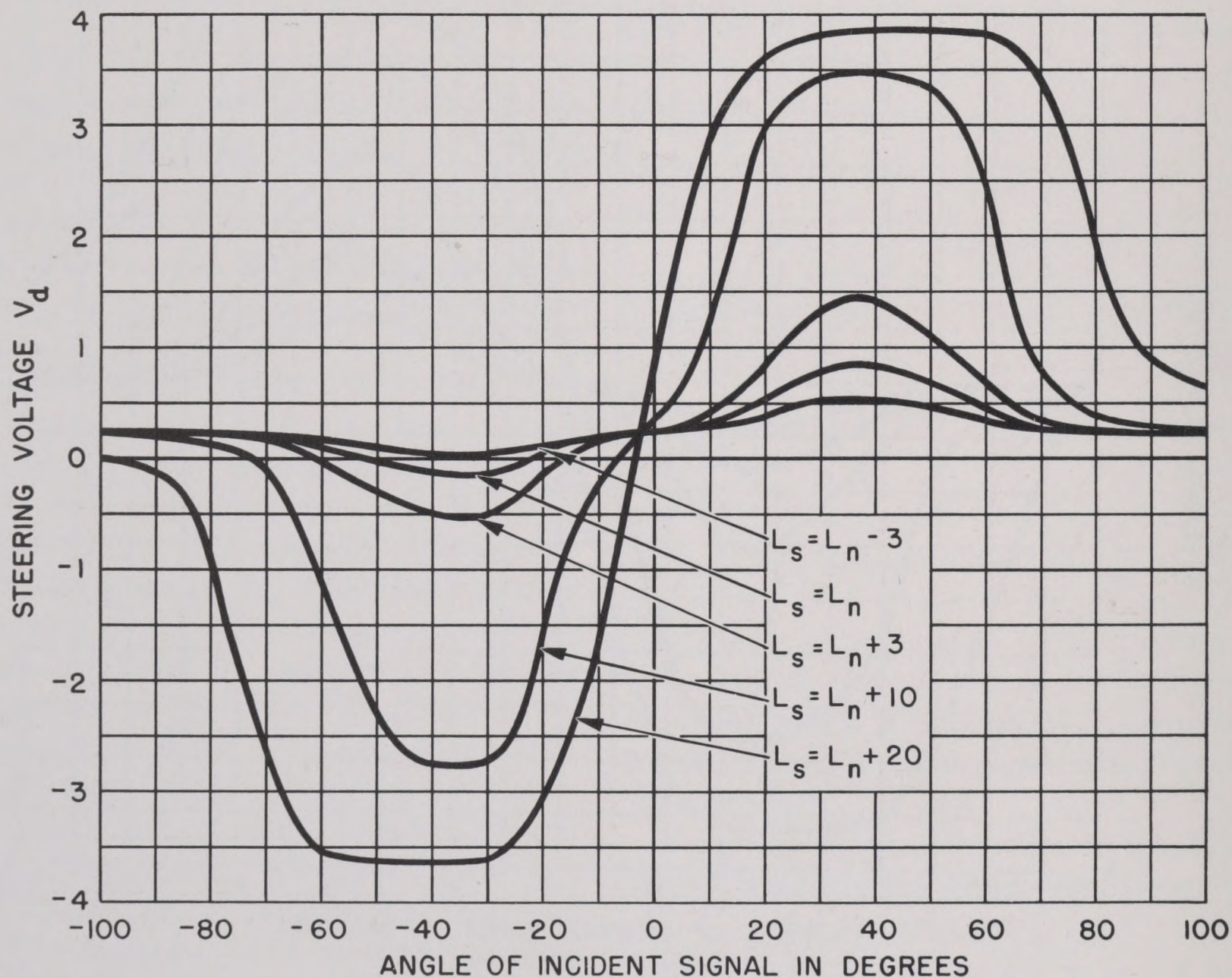


FIGURE 3. These curves represent the same situation as in Figure 2 except that the initial gain is 3 db lower.

in the next chapter, it must be kept within suitable limits. Figure 3 shows the corresponding curves when the initial gain is 3 db lower. In this case the steering voltage produced by the self noise is only 0.23 v. Figure 4 shows the curves for a 3-db higher gain.

From these curves a number of conclusions can be drawn.

1. The unbalance of the hydrophones and their amplifiers causes the torpedo to circle in the absence of a signal if the gain is set high enough so that the differential response to the self noise gives a rudder deflection. This unbalance, which is unavoidable in

self noise itself, sets a limit to the signal strength on which the torpedo can steer. It is clear from the figures that the torpedo with the properties used for this illustration will not steer on a signal strength 3 db below the noise, no matter how high the gain is set.

4. The stiffness of the control, the volts steering voltage per degree off course, increases as the gain increases, but is not proportional to the gain.

The above is essentially an illustration of a method of analysis of a typical circuit. Each circuit will have its peculiarities of behavior that must be understood



and related to the dynamical behavior of the torpedo to be described in the next chapter.

In addition to the static analysis as just illustrated it is necessary to make a dynamic analysis of the operation of the control mechanism. The previous illustration gave the rudder position as a function of the direction of the sound provided the direction was fixed and time was allowed for the rudder to reach its position. If the torpedo is oscillating and the source of sound is moving it is important to know the

For very slow oscillations, the rudder position for a given angle of sound incidence will be very close to that indicated by the static analysis and such curves as those of Figures 2, 3, and 4. For higher frequencies, however, the rudder will lag behind the sound and the amplitude of its oscillation may also diminish. As will be shown in the next chapter it is desirable to keep this lag as low as possible.

The time lag is due to a number of factors. In the first place the condensers  $C_p$  and  $C_s$  take a certain

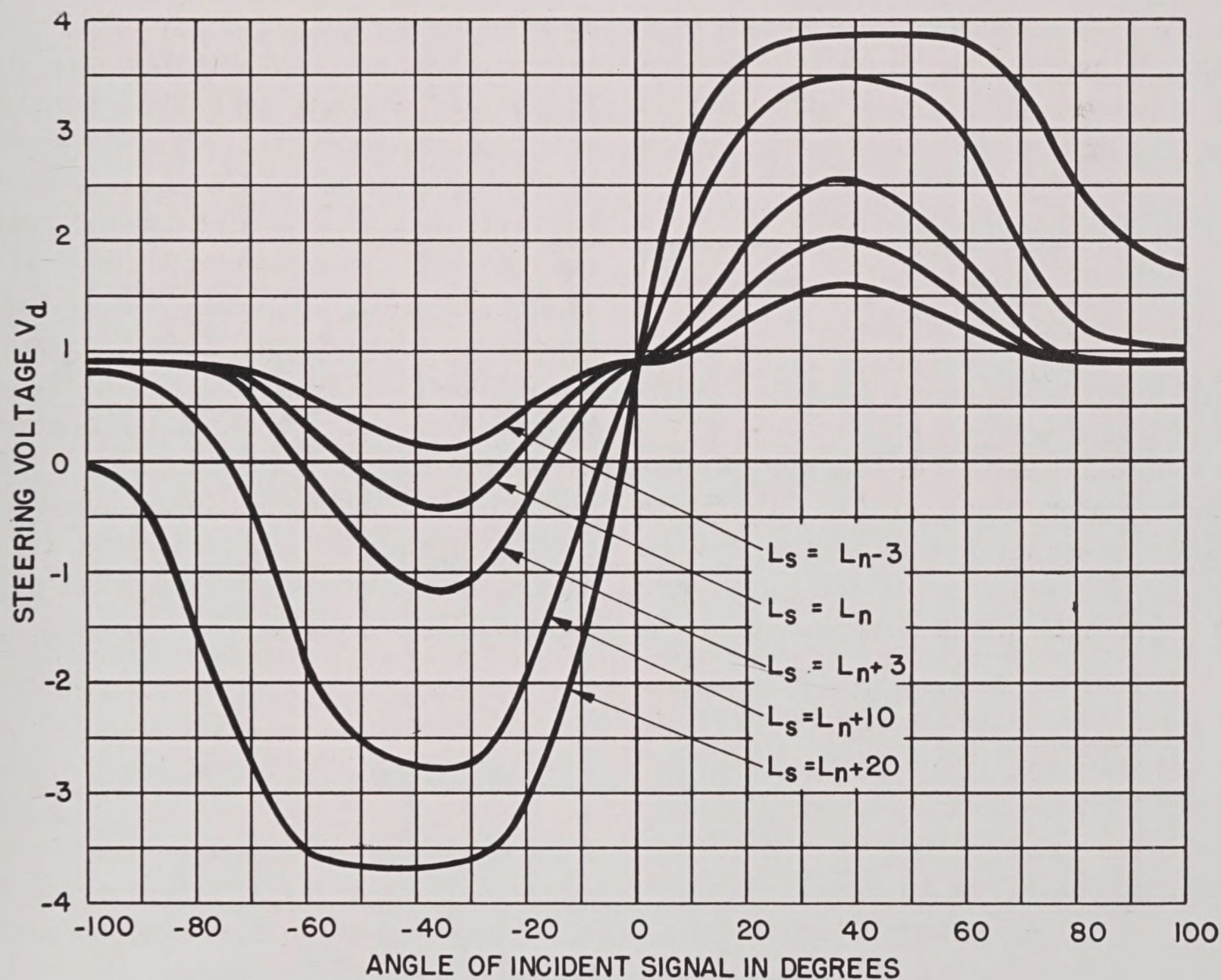


FIGURE 4. In these curves the initial gain is assumed to be 3 db higher than in Figure 2.

way in which the rudder follows the direction of the sound.

Perhaps the simplest way in which to make a dynamic analysis of the control circuit is to feed sound into the hydrophones artificially. This can be done by placing projectors close to each one, or by feeding a suitable electric signal into the hydrophone circuit. The relative intensities can be varied in such a way as to simulate a sinusoidal variation of the angle from which sound is incident on the torpedo. This variation can be carried out for a range of frequencies and the oscillation of the rudder observed.

time to charge up, and until they do charge up to their equilibrium voltage the rudder cannot reach its equilibrium position. The time necessary for this charging can be reduced by making the condensers small. This, however, must not be carried so far that the system is too responsive to short bursts of noise. Another important source of time lag lies in the rudder motors themselves. It takes them a certain time to start up and to move the rudders to the desired position. In general it is desired that the motors have a high starting torque and turn over as fast as possible but this possibility is necessarily limited by practical consideration of size and weight.

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## 8.2 OTHER TYPES OF CIRCUITS

The above analysis applies to a circuit that makes use of the difference in level of the response of two hydrophones to determine the direction of a source of sound. The two hydrophones respond differently because of their own directivity patterns as well as because of the positions in which they are mounted on the shell.

Another method of determining the direction of a sound source is by measuring the difference in time of arrival at two hydrophones, or, in the case of a sustained sound, by measuring the phase difference between the responses. This phase difference is related to the bearing  $\theta$  of the sound source by the equation

$$\Delta\phi = \frac{(360d \sin \theta)}{\lambda}, \quad (8)$$

where  $\Delta\phi$  is the phase difference in degrees,  $d$  is the separation of the hydrophones, and  $\lambda$  is the wavelength of the sound. In systems of this kind  $d$  must not be too much greater than  $\lambda$ . If  $d = \lambda$  the phase difference is 180 degrees for  $\theta = 30$  degrees and the interpretation of the results is unambiguous only for  $|\theta| < 30$  degrees. Hence it is necessary to use

either long wavelength sound or to place the hydrophones very close together.

Although this method has not been put into service in the United States, an extensive program of study on it was undertaken by the Bell Telephone Laboratories<sup>19</sup> in the region of frequencies around 1,500 to 2,500 c. Their work showed that the phase difference type of circuit could be made to operate satisfactorily with a signal-to-noise ratio roughly the same as that needed for operation of the intensity difference systems. However, it appeared that the self noise at the low frequencies studied was so high and so erratic that practical operation appeared doubtful. Presumably such a system would work satisfactorily at higher frequencies if suitable close locations for the hydrophones could be found. It does not appear, however, that there is any particular advantage in the phase-difference system. Although it might seem at first glance that a phase-difference system might operate at a lower signal-to-noise ratio than the intensity difference system, the detailed analysis shows this not to be the case. It will not operate effectively in the presence of noise whose level is significantly above that of the signal. In case, however, it is desired to operate at low frequencies for some other reason, the phase-difference system might well be the easier type to use.



## Chapter 9

# TORPEDO DYNAMICS AND STABILITY

THE PROPER application of the acoustic signal to control the torpedo requires also an analysis of the hydrodynamic behavior of the torpedo in response to its rudder. This problem has been given considerable study, and a reasonably satisfactory theory of torpedo behavior is now possible. For a detailed treatment reference must be made to the volume on torpedoes, but enough of the theory will be outlined here to indicate the significant factors and the problems involved in the application of acoustic control. These, after all, are not greatly different from those involved in any automatic steering.

In an elementary way, the reasons why torpedo and ship steering require some careful analysis may be roughly formulated as follows:

1. A torpedo, or a ship, whose rudder is in the neutral position cannot be depended upon to travel steadily along a straight course, but must be steered. A few ships and somewhat more torpedoes, if left alone will move in a circle, either to the right or to the left. The majority run in a state that might be described as similar to neutral equilibrium. If by some means they are displaced from the course they will not return to it but will take up another more or less straight course.

2. A given rudder position does not correspond to a certain direction of motion but to a certain system of forces and moments. In time, the forces associated with a rudder displacement will cause the body to take up a stable turning circle, but the transient state, before the circle is reached, is the one of importance in steering.

3. A torpedo, or a ship, does not always travel in the direction in which it is headed but frequently at a slight angle to this direction. Hence, a clear distinction must be made between the heading of the ship and the direction of motion.

Because of such matters as the above, the detailed treatment of torpedo motion is a little complicated. Nevertheless, it is possible to understand some of the significant features in a qualitative way without treating the whole problem. In an effort to make some of these points clear, the problem will be approached in several stages. The starting point is a very crude idealization in which many factors are neglected,

and a series of simplifying assumptions is made to permit an elementary solution of the problem. In successive illustrations, more and more factors will be taken into account until a reasonably satisfactory picture of the situation can be attained. The effect of the various factors will be pointed out at each stage, and the reader can pursue the more complicated analysis as far as seems to him profitable.

### 9.1 CRUDEST POSSIBLE TREATMENT OF AUTOMATIC STEERING

It is possible to recognize a number of the significant factors in automatic control by considering a very simple model and ignoring many of the complications. To this end, let  $\theta$  be the angle between the torpedo axis and the line to the target. Then assume the following.

1. The torpedo travels in the direction of its axis at the speed  $v$ . As pointed out above, this is not always true in the case of an actual torpedo, but it is close enough so that this assumption serves for the crudest possible treatment of the problem.

2. When the rudder is at the angle  $\delta$ , the torpedo is subject to a torque that is proportional to  $\delta$ . When  $\delta$  is positive, the torque is in such a direction as to cause  $\theta$  to increase. This, coupled with the previous assumption, provides the means by which the rudder controls the torpedo's course.

3. The angle  $\theta$  is small enough so that with satisfactory accuracy the distance  $h$  of the torpedo from its straight course is given by

$$h = v \int \theta dt.$$

On the basis of the above simplifying assumptions, first the case of steering in a horizontal plane and second the case of depth keeping will be discussed.

To treat the case of steering in the horizontal plane, assume that the reference direction is the direction from the torpedo to the source of sound. In the case of a torpedo under gyroscope control, the reference direction is merely the direction of the course prescribed by the gyroscope. Then the following is assumed.

4. The control mechanism is such that the rudder deflection is proportional to the angle by which the



torpedo departs from the prescribed course and is in the direction to restore the torpedo to its course.

$$\delta = -\alpha\theta.$$

Upon the basis of this assumption, combined with the first three and the fact that a body changing direction in its underwater motion experiences an opposing torque proportional to its angular velocity, the equation of motion is

$$Q\ddot{\theta} = -K\dot{\theta} + a\delta,$$

or

$$Q\ddot{\theta} + K\dot{\theta} + a\alpha\theta = 0. \quad (1)$$

In this equation  $Q$  is the effective moment of inertia of the torpedo and the entrained water. Treatments of the flow of a perfect fluid around an ellipsoid suggest that this is roughly twice the moment of inertia of the torpedo itself.  $K$  depends strongly on the shape of the torpedo. For a sphere it would be negligible, but for a torpedo it can be estimated from model studies and the observed torpedo behavior. Estimates are available for some of the standard torpedoes. The torque is  $a$  in pound feet experienced by the body when the rudder angle is one radian. Its magnitude clearly depends on the rudder area, the shape of the afterbody, the fins, the rudder location, and the velocity  $v$ . The constant  $\alpha$  represents the stiffness of control. It represents the ratio of the rudder angle to the angle of departure of the torpedo from the prescribed course  $\theta$ .

Since the constant  $K$  is always positive, equation (1) always represents a stable damped motion. No matter what may momentarily disturb the torpedo, it will eventually settle down to the prescribed course,  $\theta = 0$ . Hence  $K$  may be called a stabilizing factor. Other things being equal, the larger the value of  $K$  the less the torpedo will oscillate about its prescribed path.

On the other hand, if  $K$  is large and  $a\alpha$  is small, the torpedo will only recover from a disturbance exceedingly slowly. Furthermore, if the target is moving, a certain minimum value of  $a\alpha$  is necessary to insure that the torpedo follows the change in path with sufficient accuracy to finally strike it. Hence to insure the type of tracking that is desired, a suitable balance must be struck between the "stiffness of control"  $a\alpha$  and the damping  $K$ .

To get a similar very crude and qualitative treatment of torpedo depth keeping it is only necessary to include the effect of the departure  $h$  from the desired depth on the rudder position. Let  $\theta$  be the angle by

which the torpedo points above the horizontal,  $h$  the distance by which it is above the desired depth, and assume the following.

5. The control mechanism is such that

$$\delta = -\alpha\theta - \beta h.$$

The equation of motion is then

$$Q\ddot{\theta} = -K\dot{\theta} - a\alpha\theta - a\beta h,$$

or

$$Q\ddot{\theta} + K\dot{\theta} + a\alpha\theta + a\beta v\theta = 0, \quad (2)$$

by making use of assumption 3. This is now a third order differential equation, and the condition for stability is slightly more complicated than before. Here again the stability referred to is the property that any solution of equation (2) approaches  $\theta = 0$  as time goes on.

The first condition for stability is that all of the coefficients be positive. This is automatically satisfied in the case at hand since  $\alpha$  and  $\beta$  are made positive in the construction of the depth-keeping mechanism. The other condition for stability is

$$\frac{\alpha K}{\beta v} > Q. \quad (3)$$

Here, as before,  $K$  is a stabilizing factor, but  $\alpha$  is also. An increase of the rudder response to the angle of tilt increases the stability of the system. On the other hand, an increase in  $\beta$ , or in  $v$ , may make the control unstable. In particular, if an attempt is made to control the depth of the torpedo by using the water pressure only without reference to the tilt, i.e., by making  $\alpha = 0$ , the torpedo will be unstable, and will not keep its depth satisfactorily.

In the normal torpedo depth control there is a pendulum so arranged that a tilt of the torpedo affects the rudder position somewhat according to assumption 5 and this is a very essential part of the depth-control mechanism. It was the introduction of this pendulum that made satisfactory depth keeping possible. From the above simplified assumptions it might be expected that a mechanism responsive to  $h$  would serve as well as a pendulum. It must be remembered, however, that the above assumptions are extremely crude, and it will be shown later why such methods are subject to important limitations.

As in the case of steering in the horizontal plane, there are two opposing sets of factors. There are first the stabilizing factors, the damping coefficient  $K$  and the response to tilt  $a\alpha$ . These tend to keep the torpedo on a steady course. Then there is the re-



sponse to departures from the correct depth ( $a\beta v$ ) which reduces the stability but is necessary to correct disturbances in depth and to keep the torpedo at the correct depth. These two properties must be correctly balanced for satisfactory depth keeping.

In both of the cases just discussed the factors leading to stability and the factors leading to precise steering or depth keeping, are opposing, and a suitable compromise between them must be made in the design.

6. The control mechanism is such that

$$\delta(t) = -\alpha\theta(t - \tau).$$

The use of this assumption gives the differential equation

$$Q\ddot{\theta} + K\dot{\theta} = a\delta. \quad (4)$$

Since  $\delta$  is no longer assumed to be simply proportional to  $\theta$ , this is of a different type from equation (2) and one whose solution must be approached in a dif-

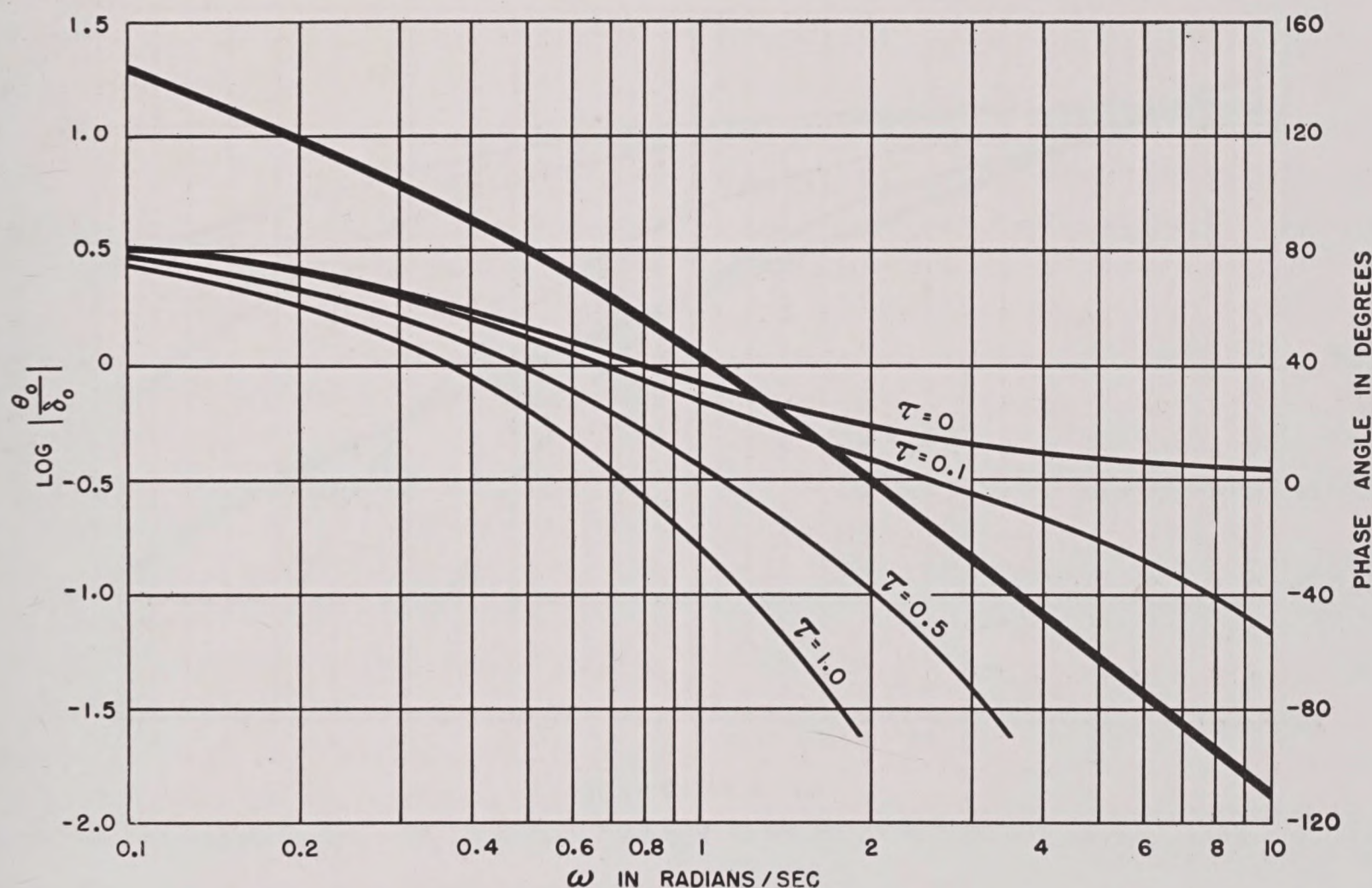


FIGURE 1. Phase in degrees as a function of  $\omega$  for several values of the time lag  $\tau$ . The heavy curve gives  $\log \left| \frac{\theta_0}{\delta_0} \right|$ . These curves assume  $Q = 1,500$  slug ft<sup>2</sup>,  $K = 10^3$  lb-ft per radian per sec, and  $a = 2 \times 10^3$  lb-ft per radian.

## 9.2 INCLUSION OF TIME LAGS IN THE CONTROL SYSTEM

In the above treatment of steering and depth control the simplifying assumption was made that the rudder position followed the acoustic or other signal exactly, without any time lag. This is rarely practicable or even possible. In the case of the circuit scheme outlined in Chapter 8, the condensers take a certain time to charge up so that the voltage  $V_d$  lags a certain amount behind the acoustic signal. In addition, the inertia of the rudder motor and the rudder itself, and the time constant of the circuit involving them, cause an additional lag of the rudder behind the voltage  $V_d$ . Hence, the crude picture is made one step closer to the actual situation by assuming for steering in the horizontal plane, that

ferent way. One method of investigating the properties of the solution is as follows.

Assume that a periodic solution exists and then find the conditions imposed upon it by the differential equation (4). Hence let

$$\delta(t) = \delta_0 e^{i\omega t} \text{ and } \theta(t) = \theta_0 e^{i\omega t}.$$

Since only the relative phases are important, assume that  $\delta_0$  is real and  $\theta_0$  is complex. Substitution in equation (4) leads to

$$\frac{\theta_0}{\delta_0} = -\frac{a}{\omega^2 Q - i\omega K}. \quad (5)$$

To satisfy the relationship assumed in assumption 6 it is necessary that

$$\left| \frac{\theta_0}{\delta_0} \right| = \frac{1}{\alpha},$$



and that

$$\frac{\theta_0 e^{-i\omega\tau}}{\delta_0} = -\frac{1}{\alpha}. \quad (6)$$

These conditions can be represented by curves of the type shown in Figure 1. For illustration, it is assumed that

$$Q = 1,500 \text{ slug feet}^2,$$

$$K = 10^3 \text{ pound feet per radian per second},$$

$$a = 2 \times 10^3 \text{ pound feet per radian}.$$

as  $\omega \rightarrow \infty$ , but as  $\omega \rightarrow \infty$ ,  $\theta_0/\delta_0 \rightarrow 0$ . At very high frequencies the amplitude of  $\theta$ , because of a unit amplitude of  $\delta$ , is so small that it will not maintain the motion of  $\delta$ , and the whole oscillation will die out.

On the other hand, for  $\tau = 0.1$  the phase is zero at  $\omega = 2.55$  where the logarithm of the absolute value is  $-0.7$ . Hence, if the stiffness is high enough, i.e.,  $\alpha = 5.0$ , the motion of the body, through the control system, will maintain sufficient rudder motion to, in turn, maintain the body oscillation. If the

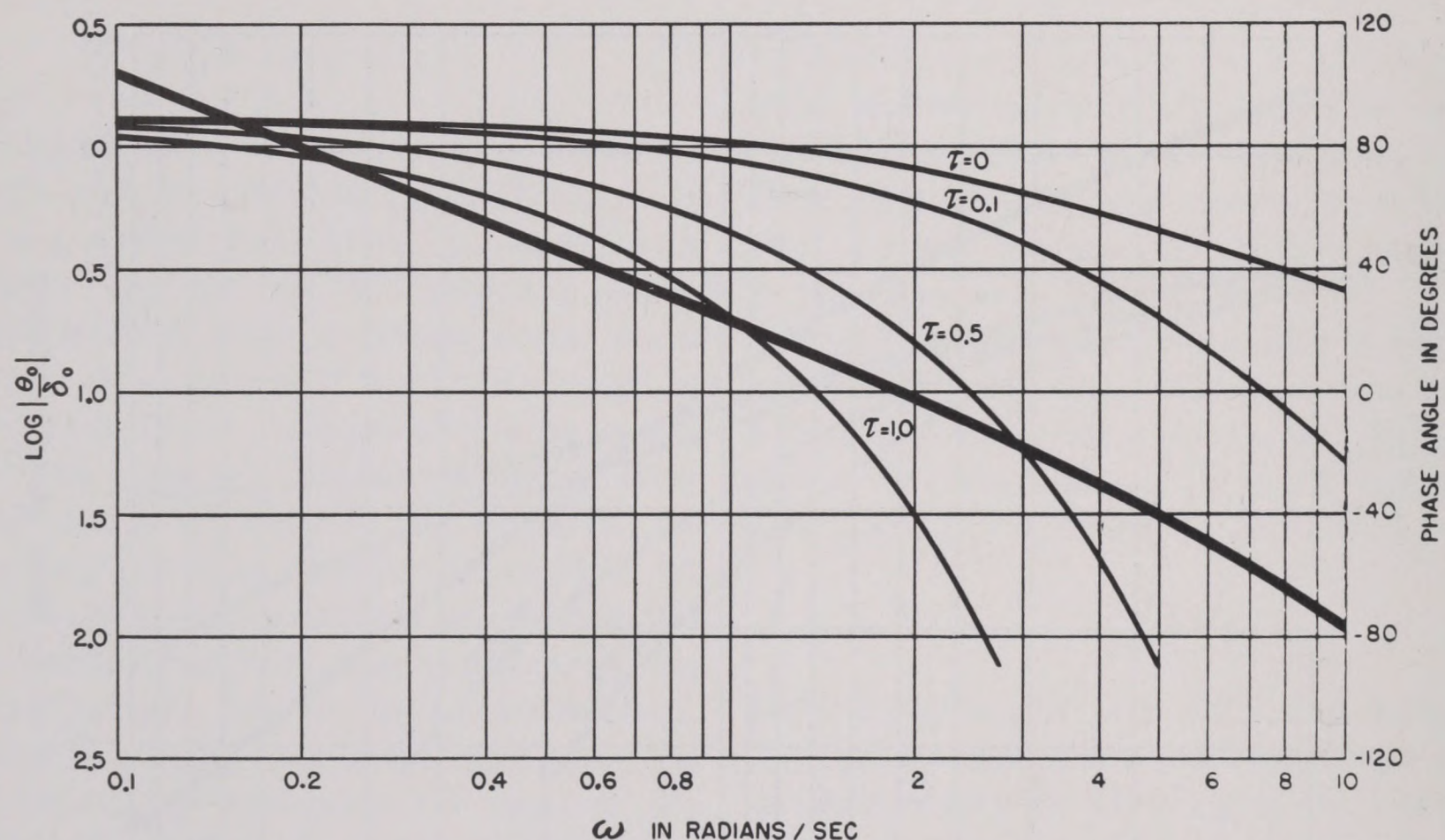


FIGURE 2. These curves are similar to those in Figure 1 but with  $K = 10^4$  lb-ft per radian per sec.

The value assumed for  $Q$ , the moment of inertia, is of the order of magnitude of that for the Mark 13-2 torpedo, as is  $a$ , the rudder torque constant. To provide an illustrative case,  $K$  is taken about 1/10 of the probable value for the Mark 13-2. The heavy curve in Figure 1 shows the absolute value of  $\theta_0/\delta_0$  as a function of  $\omega$  for values of  $\omega$  between 0.1 and 10. The ordinate as indicated in the left-hand scale is  $\log |\theta_0/\delta_0|$ . The curve shows that if  $\alpha = 1$ , equation (6) can be satisfied only for  $\omega = 1.06$ . For a stiffer control,  $\alpha = 2$ ,  $\log 1/\alpha$  is  $-0.3$ , and  $\omega = 1.57$  is the only possible value.

But it is also necessary that the left-hand side of equation (6) be real and this requires a suitable value of  $\tau$ . The phase angle is also shown in Figure 1 for various values of  $\tau$ . For  $\tau = 0$  the phase is always positive, which indicates that there can be no periodic solution. This corresponds to the stable cases treated previously in which each solution contains a decreasing exponential term. It could be described by saying that the phase approaches zero

stiffness is greater than 5.0 or the time lag is greater than 0.1 sec, the motion will build up larger and larger oscillations.

Here, then, is another destabilizing factor. The time lag in the control system as well as the stiffness of the control both tend to lead to oscillations that must be opposed by the hydrodynamic damping. Since the time lag in the control mechanism cannot be reduced to zero in most cases, a limit is set on the stiffness of control that can be used.

Figure 2 shows the corresponding curves for a damping factor 10 times as great. With this larger damping factor greater stiffnesses as well as greater time lags can be permitted and still maintain stable steering.

### 9.3 FAIRLY COMPLETE TREATMENT OF AUTOMATIC STEERING

To get anything like a quantitative treatment of torpedo steering it is necessary, as was pointed out at



the beginning of the chapter, to distinguish clearly between the direction in which the torpedo is pointing and the direction in which it is moving. To do this use the notation indicated in Figure 3. The path

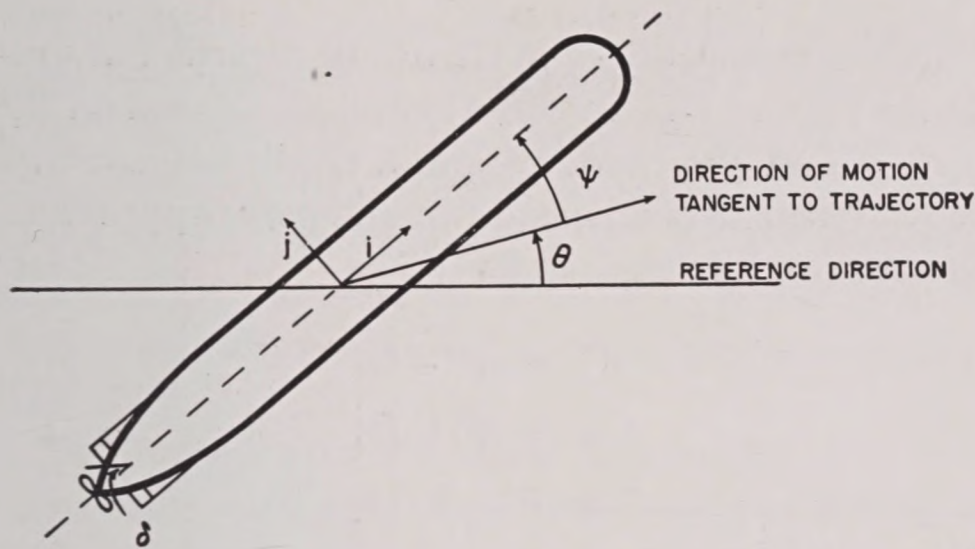


FIGURE 3. Illustration showing the notation used to describe the motion of a torpedo in the horizontal plane.

of the center of mass is taken as the torpedo trajectory and all forces and moments are considered as referred to this center. The angle  $\theta$  then describes the direction of the course, or, trajectory, with reference to a fixed direction while the angle  $\psi$  is the angle between the axis of the torpedo and the course. The rudder angle  $\delta$ , as before, is positive in the direction in which it tends to increase  $\theta$ .

As is shown in books on hydrodynamics, the inertia of a body immersed in water includes that of a certain amount of entrained water. In the case of a body somewhat ellipsoidal in shape as is a torpedo, the momentum can be described by the use of two masses. One mass applies to motion along the torpedo axis and the other to motion transverse to the axis. Referring again to Figure 3,  $\mathbf{i}$  is a unit vector in the direction of the axis and  $\mathbf{j}$  a similar unit vector at right angles to it. Then the vector momentum of the system is

$$\mathbf{M} = M_1 v \cos \psi \mathbf{i} - M_2 v \sin \psi \mathbf{j}. \quad (7)$$

Since  $M_2$  is usually larger than  $M_1$  the momentum is not in general parallel to the velocity. In computing the force necessary to change this momentum, account must be taken of the change in direction of the unit vectors,  $\mathbf{i}$  and  $\mathbf{j}$ , as well as the change of the scalar terms. This leads to the two forces, longitudinal and transverse,

$$F_l = M_1 \{ \dot{v} \cos \psi - v \sin \psi \dot{\psi} \} + M_2 v \sin \psi (\dot{\psi} + \dot{\theta})$$

$$F_t = M_1 v (\dot{\theta} + \dot{\psi}) \cos \psi - M_2 \{ \dot{v} \sin \psi + v \cos \psi \dot{\psi} \}.$$

If now it is assumed that  $\dot{v}$  can be neglected, and that

both angles and their rates of change are small quantities,  $F_t$  contains only terms of the second order of small quantities so may be considered as zero for the case of operation at constant speed. To the same approximation the transverse force becomes

$$F_t = M_1 v (\dot{\theta} + \dot{\psi}) - M_2 v \dot{\psi}. \quad (8)$$

To write the equations of motion it is necessary to define a number of hydrodynamic coefficients.<sup>20</sup> The effective forces follow.

1. The propeller thrust  $T$ . This may be treated effectively as a constant along the axis of the torpedo.

2. The drag force  $D$ . This can be expressed in terms of a drag coefficient  $C_D$ , the cross section of the torpedo in square feet  $A$ , the density of the water in slugs per cubic foot  $\rho$ , and the velocity in feet per second  $v$ .

$$D = C_D A \frac{\rho}{2} v^2. \quad (9)$$

The drag force is opposite to the velocity  $v$  and so has components both parallel and perpendicular to the torpedo axis.

3. The cross force  $L$ . This is perpendicular to the velocity  $v$ , and can be expressed in terms of a coefficient  $C_L$ .

$$L = C_L A \frac{\rho}{2} v^2. \quad (10)$$

4. A moment  $M_h$  described by a moment coefficient  $C_M$ .

$$M_h = C_M A l \frac{\rho}{2} v^2 \quad (11)$$

where  $l$  is the length of the torpedo.

5. A damping moment  $M_d$  proportional to the angular velocity of the body and described by a coefficient  $C_K$

$$M_d = -C_K l^2 A \frac{\rho}{2} v (\dot{\theta} + \dot{\psi}). \quad (12)$$

6. A transverse force associated with the damping moment and described by  $C_F$ .

$$F_d = C_F l A \frac{\rho}{2} v (\dot{\theta} + \dot{\psi}). \quad (13)$$

The drag, cross force, and the moment  $M_h$  can be measured in a water tunnel or a wind tunnel, so that the corresponding coefficients can be determined, at least approximately. They are found to depend on the angle of yaw  $\psi$  as well as on the rudder angle  $\delta$ . Such determinations are made, of course, with the center of mass moving in a straight line relative to



the water and it is assumed that the same values are approximately correct when the motion is in some other path if the radius of curvature is large enough. The coefficients  $C_K$  and  $C_F$  are taken as constants, and the presence of these terms may to some extent compensate for the errors in the assumption that equations (9), (10), and (11) apply when the body is moving in a curved path.

Taking components along the torpedo axis

$$F_t = T - C_D A \frac{\rho}{2} v^2 \cos \psi + C_L A \frac{\rho}{2} v^2 \sin \psi + C_F l A \frac{\rho}{2} v (\dot{\theta} + \dot{\psi}) \sin \psi.$$

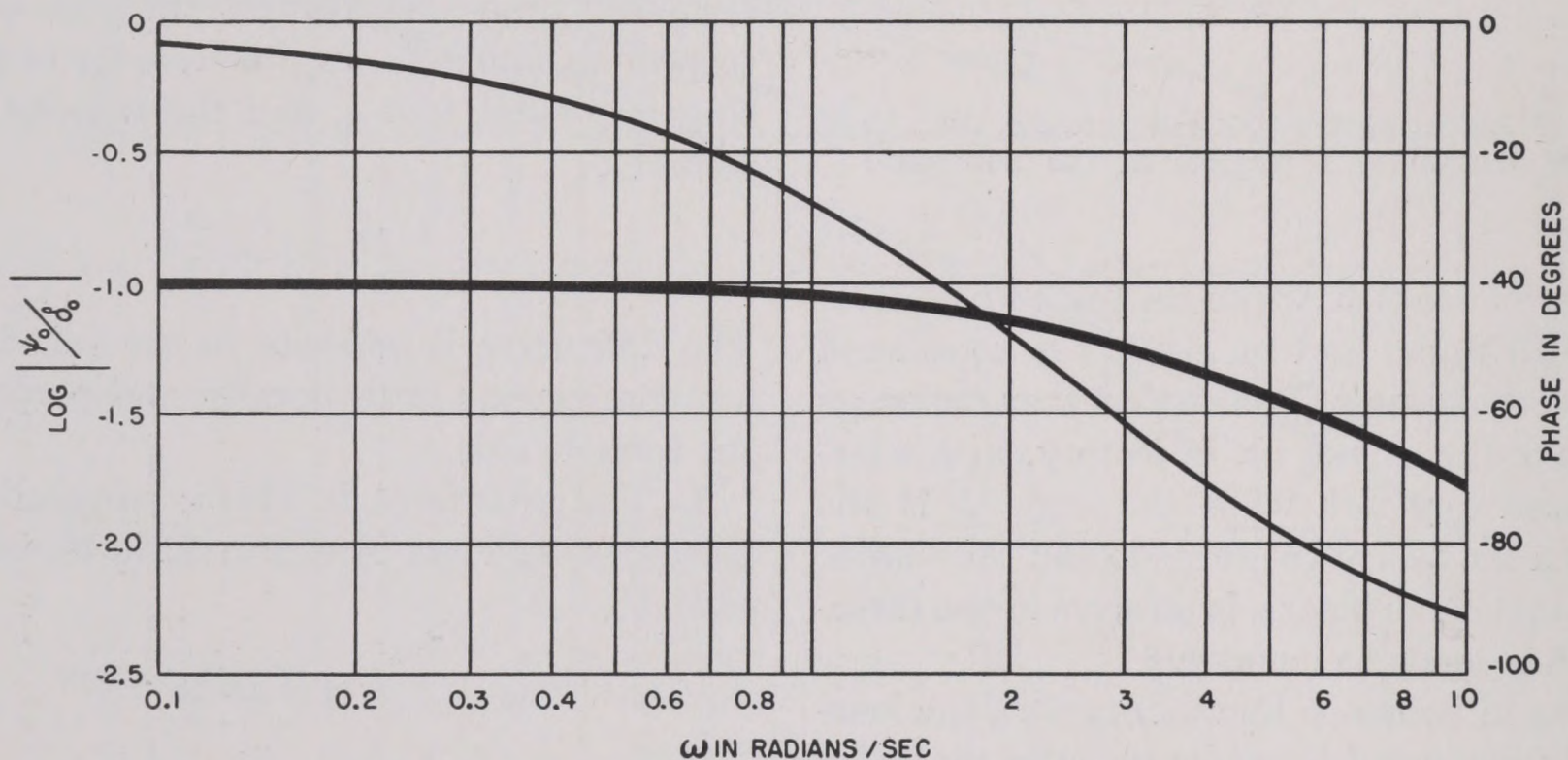


FIGURE 4. The value of  $\log |\psi_0/\delta_0|$  as a function of  $\omega$ . The heavy line gives the logarithm of the absolute value and the lighter line gives the phase in degrees.

Since the angles are assumed small, the terms containing  $\sin \psi$  can be neglected compared with the first two. Equating the first two to zero gives the speed in terms of the propeller thrust when the variations in  $v$  are neglected. This equation can then be omitted from the further considerations of steering.

The components of force perpendicular to the torpedo axis lead to

$$F_t = C_D A \frac{\rho}{2} v^2 \sin \psi + C_L A \frac{\rho}{2} v^2 \cos \psi + C_F l A \frac{\rho}{2} v (\dot{\theta} + \dot{\psi}) \cos \psi. \quad (14)$$

All of these terms are of the same order because  $C_L$  is proportional to  $\psi$ . Using expression (8) for  $F_t$  in equation (14), and equating the moments to the moment of inertia times the angular acceleration leads to two differential equations of motion

$$\left( \frac{2M_1}{\rho A v} - \frac{C_F l}{v} \right) (\dot{\theta} + \dot{\psi}) - \frac{2M_2}{\rho A v} \psi - C_D \psi - C_L = 0. \quad (15)$$

$$\frac{2Q}{\rho A v^2} (\ddot{\theta} + \ddot{\psi}) + \frac{C_K l^2}{v} (\dot{\theta} + \dot{\psi}) - C_M l = 0. \quad (16)$$

The coefficients  $C_K$  and  $C_D$  can be regarded as constants.  $C_L$  and  $C_M$ , on the other hand, depend on the angle  $\psi$  and the rudder angle  $\delta$ . Observations show that a linear dependence is an adequate approximation for small angles, so let

$$\begin{aligned} C_L &= a\psi - b\delta \\ C_M &= c\psi + f\delta, \end{aligned} \quad (17)$$

where  $a$ ,  $b$ ,  $c$ , and  $f$  are constants. When these forms are inserted in equations (15) and (16) the result can be written

$$\begin{aligned} A_1 \dot{\theta} + B_1 \ddot{\psi} + B_2 \psi &= -\delta \\ A_2 \theta + A_3 \dot{\theta} + A_2 \ddot{\psi} + A_3 \dot{\psi} + B_3 \psi &= \delta, \end{aligned} \quad (18)$$

where

$$A_1 = \frac{\left( \frac{2M_1}{\rho A v} - \frac{C_F l}{v} \right)}{b}$$

$$A_2 = \frac{2Q}{\rho A v^2 f l}$$

$$A_3 = \frac{C_K}{v f}$$

$$B_1 = \frac{\left( \frac{2M_1}{\rho A v} - \frac{C_F l}{v} - \frac{2M_2}{\rho A v} \right)}{b}$$



$$B_2 = -\frac{(C_D + a)}{b}$$

$$B_3 = -\frac{c}{f}$$

The above equations give the motion of the torpedo in response to a prescribed rudder angle  $\delta$ , and it will be assumed that the same equations hold when  $\delta$  is changing. To apply acoustic control,  $\delta$  must be made some function of  $(\theta + \psi)$ . A fair representation can be obtained by making  $\delta$  proportional to  $-(\theta + \psi)$  with a time lag as was done in a simpler case above.

To proceed with the study of equation (18) it is convenient to assume a periodic value of  $\delta$ , and to find the corresponding periodic solution for  $\theta$  and  $\psi$ .

stants will be assumed. They are approximately those applicable to the Mark 13 torpedo with a shroud ring.

$M_1 = 67$ slugs	$f = 0.0573$
$M_2 = 116$ slugs	$l = 13.5$ ft
$v = 50$ ft per sec	$C_D = 0.10$
$A = 2.75$ sq ft	$Q = 1,500$ slug ft <sup>2</sup>
$\rho = 2$ slugs per cu ft	$A_1 = 1.67$
$C_K = 0.50$	$A_2 = 0.282$
$C_F = 1.10$	$A_3 = 2.36$
$a = 2.23$ per radian	$B_1 = -5.73$
$b = 0.114$ per radian	$B_2 = -20.4$
$c = 0.281$	$B_3 = -4.90$

Figure 4 shows the value of  $\psi_0/\delta_0$  as a function of  $\omega$ . If the rudder is turned back and forth with a

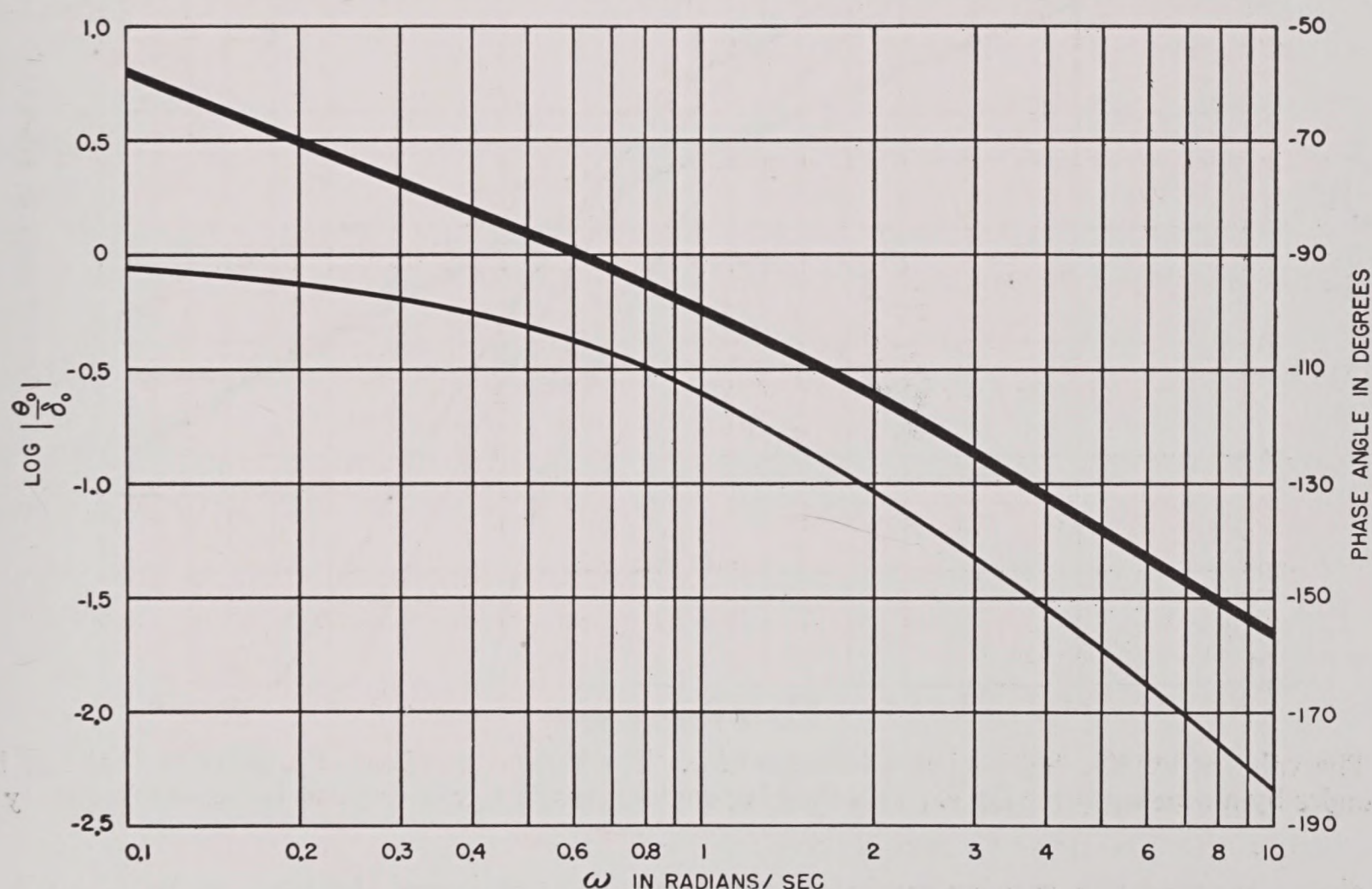


FIGURE 5. The value of  $\log |\theta_0/\delta_0|$  as a function of  $\omega$ . As previously the heavy line shows the absolute value and the lighter line gives the phase.

Hence let  $\delta = \delta_0 e^{i\omega t}$ ,  $\theta = \theta_0 e^{i\omega t}$ ,  $\psi = \psi_0 e^{i\omega t}$  where  $\delta_0$  is real but  $\theta_0$  and  $\psi_0$  are complex. Insertion in equation (18) then leads to

$$\frac{\psi_0}{\delta_0} = \frac{\{A_1 + A_3 + i\omega A_2\}}{\Delta}$$

$$\frac{\theta_0}{\delta_0} = -\frac{\left\{A_3 + B_1 + i\left(\omega A_2 - \frac{B_2 + B_3}{\omega}\right)\right\}}{\Delta}$$

$$\Delta = \{A_1 B_3 - B_2 A_3 - \omega^2 (A_1 - B_1) A_2\} + i\omega \{(A_1 - B_1) A_3 - A_2 B_2\}$$

For illustration the following values of the con-

sinusoidal motion having an amplitude of 10 degrees and a frequency of 0.0159 c ( $\omega = 0.1$ ) the angle  $\psi$  will vary sinusoidally with the same frequency, a phase lag of 3 degrees, and an amplitude of about 1.0 degree. At this slow rate the amplitude of  $\psi$  is nearly the equilibrium value of  $\psi$  if the torpedo were in a steady turn with the given rudder amplitude as a fixed rudder angle.

If the frequency of the rudder motion is made ten times as great ( $f = 0.159$ ,  $\omega = 1.0$ ) the amplitude through which  $\psi$  oscillates is still about the same but the phase lag has become some 28 degrees. When the frequency is again multiplied by 10 ( $f = 1.59$ ,  $\omega = 10$ ),



the amplitude of  $\psi$  is 0.18 degree and the phase lag has become over 90 degrees. At this frequency the torpedo turning is always in the transient state and steady turning conditions never get a chance to develop.

The behavior of the angle  $\theta$ , is a little different as is shown in Figure 5. For low frequencies it can become much larger than the rudder angle since the torpedo keeps on turning as time goes on. At the frequency of 0.0159 c ( $\omega = 0.1$ ) the amplitude of  $\theta$

oscillates with a large amplitude. On the other hand if the rudder is moved rapidly back and forth  $\psi$  follows it to some extent, but  $\theta$  is hardly affected at all. When a torpedo starts to turn,  $\psi$  increases first and then  $\theta$  follows, but if the direction of the motion is soon reversed there is not time for any significant variation in  $\theta$ .

An acoustic control will respond only to the sum of the angles ( $\theta + \psi$ ), hence it is important to see how this behaves. Figure 6 shows the amplitude and phase

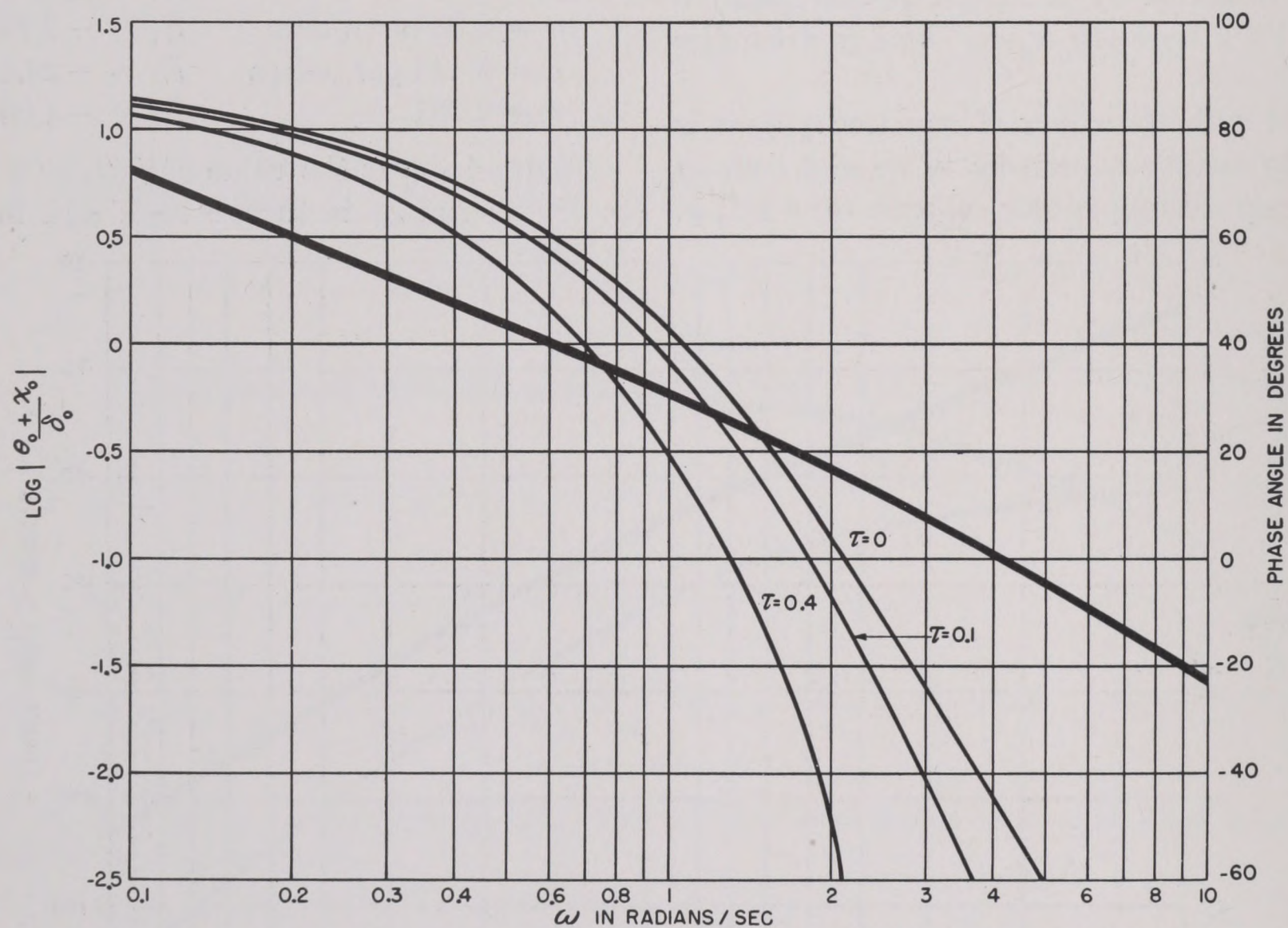


FIGURE 6. The value of  $\log |(\theta_0 + \psi_0)/\delta_0|$  as a function of  $\omega$ . In addition the phase of a quantity that lags behind the sum of the angles by a constant time lag  $\tau$ . This time lag corresponds to a greater phase lag as the frequency increases.

is about 6.3 times that of the rudder angle. If the rudder is being oscillated with an amplitude of 10 degrees, the 63-degree amplitude of  $\theta$  would contradict the original assumption that all angles are small and the differential equations would no longer apply. If, however, the rudder amplitude were made small, say 2 degrees, the method would be applicable. Under these circumstances the angle  $\theta$  lags some 92 degrees behind the rudder angle  $\delta$ . As the frequency is increased the amplitude of  $\theta$  becomes rapidly smaller so that for  $\omega = 10$  it is only 1/50 that of  $\delta$  and somewhat more than that of  $\psi$ . The phase lag is also near 180 degrees.

These curves illustrate the ways in which the two angles  $\theta$  and  $\psi$  behave when the rudder is oscillated. If it is swung slowly,  $\psi$  reaches a limiting value but  $\theta$

of the negative of the sum,  $-(\theta_0 + \psi_0)/\delta_0$ . The phase is given by the curve marked  $\tau = 0$ . If the position of the rudder is made proportional to  $-(\theta_0 + \psi_0)$  and there is no time lag, the system will be stable and a large stiffness can be used. This is shown by the fact that the curve marked  $\tau = 0$  crosses the axis of zero phase shift at  $\omega = 2.2$  where  $\log |(\theta_0 + \psi_0)/\delta_0| = -0.6$ . If, however, the almost unavoidable time lag is taken into account, restrictions are at once placed on the stiffness. The curves marked  $\tau = 0.1$  and  $\tau = 0.4$  show the phase of the rudder oscillation if it lags at time  $\tau$  behind  $(\theta + \psi)$ . If the time lag is 0.4 sec the phase becomes zero for  $\omega = 1.3$ . This means that if the rudder is oscillated at such a rate, the motion of the body will be such as to just maintain this oscillation when the coefficient of propor-



tionality is properly chosen. Figure 6 shows that for  $\omega = 1.3$  the amplitude of the torpedo motion will be about 0.4 as much as that of the rudder. If then the stiffness is such that 0.4 degree torpedo angle produces 1 degree rudder angle the motion will just be maintained. A smaller stiffness will lead to the type of stability in which the oscillations will die out while a greater stiffness would cause the oscillations to increase without limit.

#### 9.4 GENERAL CONCLUSIONS

The above examples illustrate the way in which the response of a torpedo to a control system can be analyzed. The constants describing the behavior of the body must be obtained from measurements in a water tunnel or a wind tunnel and by a study of the turning characteristics of the body. The description of the control system including such things as the stiffness and the time lag must be determined either from actual measurements on the system or by calculations on the basis of the design. The above illustrations are cases of a "proportional" control, in which the rudder position is proportional to the displacement of the torpedo from the prescribed direction. It is possible, however, to apply similar analysis to cases in which the rudder is put hard over in either one direction or the other. The details of such sys-

tems will not be worked out here but in general it appears that the limitations on stiffness and time lag are a little more severe than with the proportional systems.

In general it is clear that "steering" and "stability" are somewhat contrary requirements. To steer easily a torpedo should respond quickly and vigorously to any departure from its prescribed course. This is produced by a stiff control system, by large rudders, and by a short radius of turn. On the other hand these factors tend to make a body overshoot its course and to oscillate widely about the desired path. To provide stability on a course, the correction of departures from it must be tempered by limiting the stiffness and the rudder area, by limiting the sharpness of turn, and in addition, by shaping the body so as to produce large damping forces. A suitable compromise must be reached between the factors leading to good steering and those leading to stability on the course.

In addition to the opposing sets of factors leading to good steering and to stability, a time lag in the control system always leads toward instability without producing any improvement in steering. As a consequence, it is necessary to keep the time lag as small as possible since stability in the presence of a large time lag can be obtained only at the expense of steerability.



## Chapter 10

### MISCELLANEOUS PROBLEMS

IN THE DETAILED application of the principles that have been described in the previous chapters there are many points that must be given careful study, and engineering skill of the highest order must be put into the design in order to produce a practical, workable, and rugged mechanism. Solutions of many of these problems can be recognized in a study of the accepted designs and specifications, and will not be discussed here. In this chapter only a few of the problems that are of general importance will be mentioned.

#### 10.1 BALANCING THE AMPLIFIERS

In the circuit described in Chapter 8 it is necessary that the two amplifiers be closely balanced and that this balance be maintained over a very wide range of signal strengths. The most obvious way to try to do this would be merely to design and construct both amplifiers so carefully that the balance could be established once and for all, and would not change. This, however, is difficult for the large values of gain required, the type of service under which a torpedo must stand up, and the necessity of occasional changes of tubes. It has been used in the ExFER42 mine as developed by the General Electric Company and manufactured by the Leeds and Northrup Company. In this circuit the gain of the amplifiers that must be accurately balanced is considerably less than in other circuits and, although extensive service tests of this device have not yet been made, it appears to be capable of satisfactory operation.

Two other methods have been successfully used in acoustically controlled torpedoes and will be briefly indicated here.

##### 10.1.1 A Switching Scheme

This method consists in using the same amplifier for both hydrophones and switching the amplifier rapidly from one to the other. In the first experimental models of the ExF42 mine this switching was done mechanically by a rotating commutator.

Figure 1 shows the schematic arrangement of such a system. The two commutators are driven by the same motor so that both the amplifier and the rectifier are switched from one hydrophone circuit to the other. The rate at which the commutation takes place must be adjusted to the other properties of the control circuit. In the experimental model of the ExF42 mine the commutation was carried out at a rate of 40 c. It was then necessary to make the time constant of the AVC so long that it did not act on the difference in response of the two hydrophones and so tend to smooth out this differential. This commutation frequency is also a frequency of modulation of the incoming signal so that it sets a limit

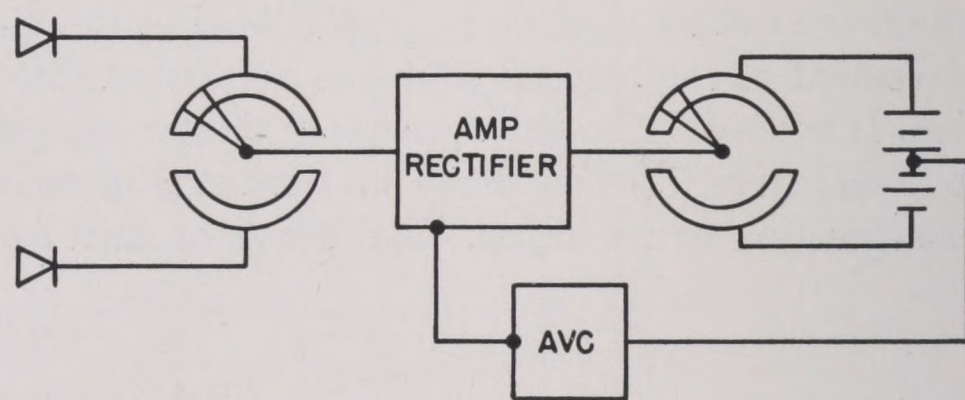


FIGURE 1. Schematic diagram of a mechanical switching system by means of which a single amplifier and rectifier can be used in two channels.

to the sharpness of tuning possible in the amplifier circuit. With suitable adjustment of the various time constants this commutation system worked quite satisfactorily although it is not very suitable for Service use.

In the final form of the ExF42 mine the commutation was carried out electronically and at a considerably higher rate. This system, free from moving parts, was felt to be much more satisfactory for field use. In general, the switching method solves the problem of balancing the amplifiers, but it introduces additional difficulties associated with the switching equipment and the proper adjustment of time constants. However, these problems can be satisfactorily solved as is evidenced by the performance of the ExF42 circuit.



### 10.1.2 A Pilot Channel System

This method, which has shown satisfactory performance in experimental operation, provides monitoring of each channel by a signal of a frequency that can be filtered out of the amplifier output and used to operate volume controls. Figure 2 shows a schematic diagram of this kind of system. A single 2-kc oscillator feeds a signal into both circuits along with the signals from the hydrophones. After passing through the amplifiers, the different frequency signals are separated and the 2-kc signals are main-

signal reaches a predetermined level at which vertical steering begins. Operations of this kind can be carried out by means of relays that are then called "gates." It is possible to operate a gate on the sound differential as well as the sound level so that the torpedo steers on its gyro course until the differential between the hydrophones attains a predetermined value. This type of gate permits operation at a somewhat lower level and also keeps the torpedo under gyro control as long as it is headed closely at the target.

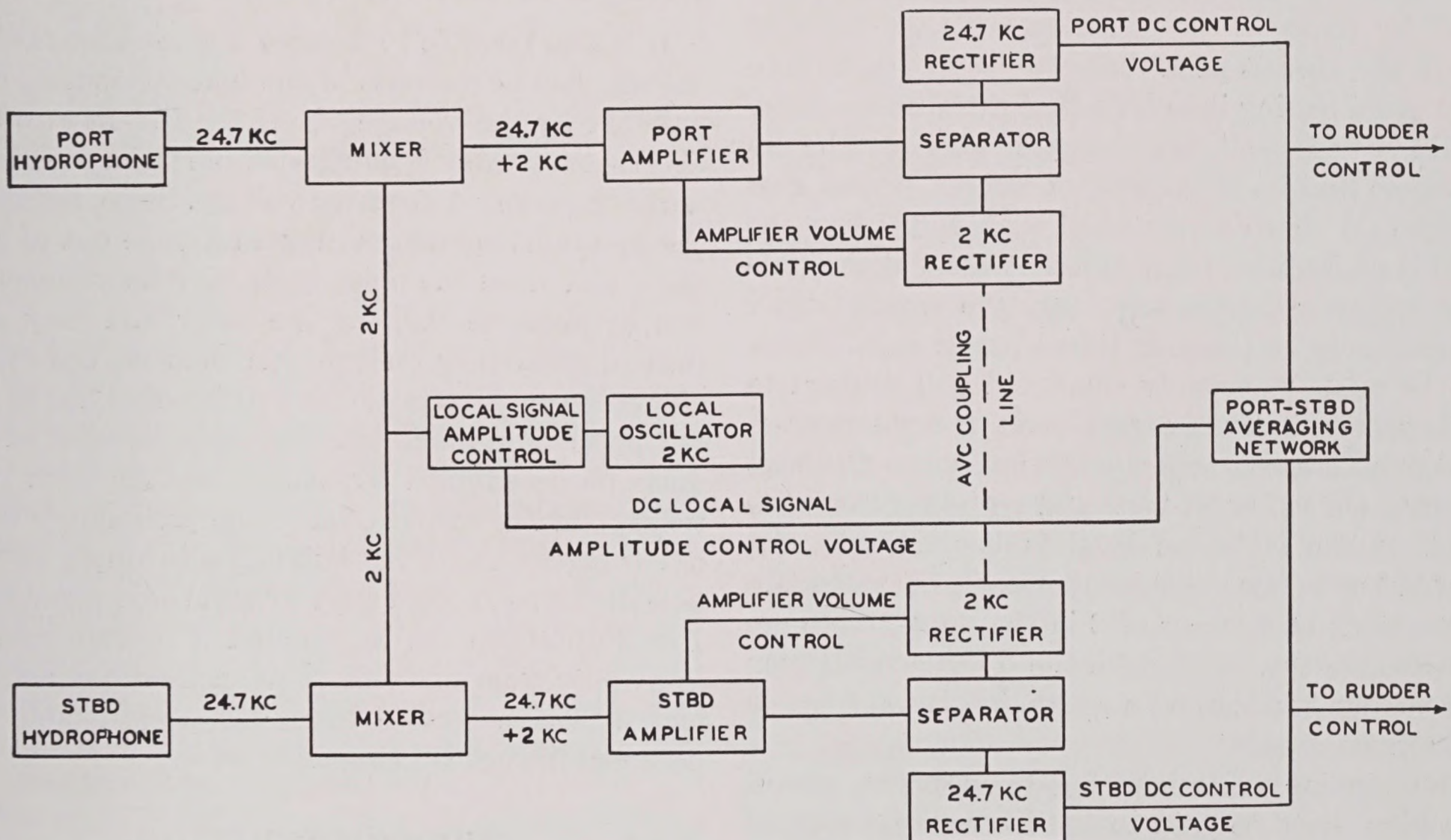


FIGURE 2. Block functional diagram of a pilot channel amplifier circuit as developed by the Harvard Underwater Sound Laboratory.

tained constant and equal by their respective AVC systems. The overall gain of the amplifiers is controlled by changing the level of the 2-kc input into both channels. This circuit also requires careful design but it has shown satisfactory operation in experimental models built by the Harvard Underwater Sound Laboratory [HUSL].

## 10.2 GATE OPERATION

In many cases it is desirable to have the torpedo operate on a preset gyro course until the sound from the target has become sufficiently intense to give adequate control. In other cases it is desirable to steer in azimuth only, at a fixed depth, until the

### 10.2.1 Level-Operated Gate

The average sound level is given by the potential at the point *P* in Figure 1 of Chapter 8. This can be connected to a relay through a triode if desirable, in such a way that the relay operates when  $V_p$  reaches a predetermined value. The relay can be such that it will open again when  $V_p$  drops, or it can be such as to lock closed after it has once operated. When a level-operated gate is used to transfer from gyro steering to acoustic steering, the adjustment must be such that the gate does not operate on self noise, for then the torpedo would go into a circle as described in Chapter 8 and would not continue to approach the target. On the other hand, the gate



should not require such a high level to operate it that the effective homing range is too short.

If the torpedo self noise were entirely constant in time, so that the potential  $V_p$  due to it were maintained constant, the gate could be set to operate at a level only a trifle above that of the self noise. However, this is rarely the case. The noise tends to fluctuate and may contain modulation frequencies corresponding to the revolutions of the propeller. It is then necessary to set the gate to operate sufficiently high above the average background level that it is not operated, or at least is not often operated, by peaks in the noise level. To set the gate above the highest peak that can occur would probably mean setting it so high that the acoustic range would be too small, but the gate circuit can be designed so that its time constant will not permit it to operate on sharp peaks at all but only when the level is maintained for a sufficient time. If the time constant were indefinitely long, the circuit would respond only to the long time average level, but it can be made reasonably short and still respond to fairly representative average levels. It appears practical to set a gate to operate at some 5 or 6 db above the average self-noise level and get satisfactory results. If the self-noise level is low enough, this wasted 5 or 6 db is of little importance, but since 6 db corresponds to a factor of 2 in the range, there are cases where this may make the difference between satisfactory homing and a range that is too short to be of much use.

In designing a circuit with gate operation, careful attention must be paid to the interrelationships of the various time constants. These are associated with the steering circuit, the AVC circuit, and the gate circuit. In the simple circuit shown in Figure 1 of Chapter 8 the time constant associated with  $V_d$  is the same as that of the AVC, but this need not be the case. Presumably, the maximum gain of the amplifiers will be set so that the AVC will not be called into operation by the torpedo self noise and the time constant of the steering circuit will then be made long enough to average out fluctuations in this noise but not long enough to introduce significant instability into the steering. An additional length of time constant can then be introduced into the AVC since the average response of the two hydrophones will change more slowly than the differential when the body is oscillating about its course.

In some cases it has been found that the noise from a surface ship is strongly modulated at a rather

low frequency corresponding to a propeller blade frequency. In such a case it may be undesirable to use a time constant long enough to average out this modulation because of the sluggishness that would be introduced into the system. On the other hand, it is also impossible to have the gate relay opening and closing several times a second until the minima are sufficient to operate it. Under such circumstances, the gate may require still a third time constant to control its operation.

### 10.2.2 Differential-Operated Gate

It is also possible to arrange a gate to operate on the differential response of the hydrophones as represented by the voltage  $V_d$ . If the response to self noise were entirely symmetrical, the self noise would never cause any differential voltage. Since, however, the hydrophone circuits may be a trifle out of balance, and since the noise itself may be stronger at one hydrophone than at the other and may also pulsate differently on one side than on the other, allowance must be made for a differential due to the self noise. The minimum that must be allowed for must be determined by experiments on each particular kind of torpedo, but some preliminary tests have suggested that 3 to 4 db might be ample. In this case the torpedo could start to home on a signal only 1 or 2 db above the background if it were coming essentially from one side. This method has not yet had extensive service tests, but considerable experimental work is being done on it.

## 10.3 RUDDER OPERATION

The rudders of a torpedo may be operated in a number of ways. Most conventional, nonhoming torpedoes use compressed air for this function, but since acoustic homing devices require electric circuits and electric energy, electrical rudder operation is frequently used. One method makes use of rudder motors. This is suggested by analogy with the steering of large ships where motors are often used to move the rudders. The first ExF42 mine used this system, and the experience gained in this way has brought to light a number of disadvantages.

In order to get sufficient power without a very heavy motor it is necessary to operate the motor at high speed, and to drive the rudders through a reduction gear. This tends to produce noise and may be the limiting source of noise in the ExF42 mine. Furthermore, it is difficult to get sufficient quickness

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of response because of the time necessary to accelerate the motor and gear system. This latter factor was found to be one of the principal elements in the time lag of the control system. On the other hand, rudder motors seem well adapted to a positioning system, since they can move the rudders to the desired position and then stop.

Another method that has been used in the Ex20F torpedo involves the use of solenoids for pulling the rudders one way or the other. This provides quick action but involves the use of heavy currents, which are somewhat troublesome to handle, and greater weight. For a system in which the rudders are thrown one way or the other, this may be the simplest procedure but the use of solenoids for a positioning system seems less straightforward, although it can be done.

#### 10.4 STEERING IN DEPTH

For an antisubmarine torpedo the problem of steering in depth as well as in azimuth must be solved. Furthermore, the discovery of cavitation as a principal source of torpedo noise suggested at once that the acoustic homing range could be much increased by normally using a running depth of from 50 to 100 ft. To attack a surface target it is necessary for the torpedo to come up at the target in just the right way to hit it. This presents problems of dynamics and control quite different from those met with in ordinary torpedo practice, and problems that are not yet fully understood. Just a few aspects of the matter will be mentioned here.

One of the difficulties arises in connection with the stability of the torpedo with reference to heel, particularly in the case of a torpedo with a single propeller. In this case the propeller torque is balanced by the torque associated with a displaced center of mass, and the torque is balanced only when the torpedo axis is horizontal. If the torpedo should travel vertically upward, there would be no torque compensation at all, and the torpedo would begin to

spin. This suggests that means must be provided to limit the angle of climb or dive to such small value that no untoward spinning can occur.

Another associated difficulty can be illustrated by considering the case of motion in a circle. If the rudders are put hard over to port, the torpedo takes up a circular motion and continues to turn in this circle as long as power is available. If, however, the elevators are put hard up, the torpedo starts to turn in a circle in a vertical plane. Before it has completed 180 degrees it is upside down and will probably turn over, whereupon instead of completing its circle it starts up again.

Another difficulty with vertical steering is the presence of the surface. When maneuvering in a horizontal plane, the torpedo can oscillate from side to side of its course and if it misses the target it can turn around and try again. If, however, it oscillates too widely in the vertical plane, it may jump clear out of the water and will return by falling back rather than by following the course prescribed by the controls.

It seems that most of the methods thus far used for overcoming or avoiding these difficulties in vertical steering can be described as means for reducing maneuverability in the vertical plane and requiring the sharp turning to be done by means of the rudders for steering in azimuth. This can be done by means of a climb angle limiter in the form of a pendulum that takes control when the inclination exceeds a certain maximum and cuts out or reduces the effect of the acoustic signal. Another method consists in requiring the vertical acoustic control to oppose the hydrostatic and pendulum depth control so that the torpedo can climb steeply only under a very strong signal. To keep the torpedo from rising too soon the sensitivity in the vertical channel may be reduced below that in the horizontal channel. Most of these methods are palliative, and it seems that the problem of steering in depth still awaits a complete analysis and solution.



## Chapter 11

### SIGNAL AND NOISE LEVELS IN HOMING BY ECHO RANGING

IN A torpedo to be controlled by echo ranging, a sound signal is radiated by a projector located in the torpedo, and the echo returned from a reflecting body in the neighborhood is used to steer the torpedo. Some of the problems involved in this type of control may be listed as follows.

1. The projector must radiate into the water enough sound energy so that the returned signal can be distinguished from the background and self noise. The signal must also be radiated in a wide enough solid angle to reach any expected targets.

2. The listening mechanism must be such as to identify the direction from which the echo is returned. It must not be put out of commission by the periodic operation of the powerful transmitter, and it must, as far as possible, distinguish the desired echo from undesired echoes such as reverberation and bottom echoes.

3. The steering mechanism must be such as to direct the torpedo on the basis of the intermittent information obtained from the echoes. This is a somewhat different matter from steering on the continuous information available to a listening torpedo.

The remainder of this chapter will be devoted to a discussion of the problems of the projector.

Let  $P$  represent the total power in watts radiated by the projector into the water. One of the principal advantages of the echo-ranging method is the fact that this quantity is to some extent under the control of the designer. In general it is desired to make this as large as possible, so that some attention must be given to the factors that limit it. One of these factors is cavitation at the surface of the projector. If the minimum pressure in the sound wave gets down to the neighborhood of the vapor pressure, cavities will be formed into which the liquid evaporates and gas comes out of solution. This begins to occur in the neighborhood of  $\frac{1}{3}$  watt per sq cm in water at about two atmospheres pressure. Observations by the Bell Telephone Laboratories [BTL], however, have indicated that this figure can be much exceeded for very short pulses. Apparently, if a pulse

length of about 1 to 5 msec is used, the cavitation does not have time to develop and more power can be radiated than with longer pulses. The BTL projector for trial in the Mark 14 torpedo was thought to be radiating close to 1,000 watts. This is much above the  $\frac{1}{3}$  watt per sq cm and is possibly near the practical limit for transducers suitable for use in a torpedo.

As indicated in the previous paragraph, more energy can be radiated from a large projector than from a small one. A large projector, however, tends to have a narrow beam pattern which may, under some circumstances, be undesirable. It is necessary to have a pattern that directs sufficient energy off the axis to reach the desired targets. Hence, it may be desirable either to use a small projector or to direct the beam so as to scan the desired solid angle. In this connection, systems in which energy is radiated first to one side and then to the other side of the axis have been suggested by the British. If arrangements are made so that the torpedo itself moves in a circle, the beam scans a large region even though it itself is narrow. The turning must be at a rate slow enough so that the beam does not sweep over the target between pulses. Such a method is used in the ExFER42 mine. However, in case the torpedo starts out on a gyro-controlled course, the beam pattern must be wide enough to reach the target unless a searching procedure is introduced at a predetermined range.

If the beam pattern is specified in advance, the wavelength and the linear dimensions of the hydrophone must be kept proportional to each other. Hence, since the power that can be radiated is proportional to the area, the level that can be produced at the target increases with wavelength. To get a high signal level a large projector and a correspondingly long wavelength should be used. In case the pattern is not specified, the highest level is produced by the narrowest pattern. This implies a large projector but a short wavelength.

Another practical limit on the radiated power is the size and weight of the apparatus necessary to



drive the projector. Projectors are rarely more than 50 per cent efficient and sometimes are as low as 20 per cent so that from two to five times the power radiated must be supplied. If a very short pulse length is used, this power can be obtained from a storage condenser so as to keep the average rate at which electric power is supplied relatively low.

The important thing about the returned echo is not particularly its total energy but its spectrum level. If the energy is contained in a very narrow band of frequencies, and a sharply tuned receiver is used, the signal-to-noise ratio can be made higher than otherwise. However, if a short ping is used, the frequency band cannot be made too narrow. With a suitable definition of the band width  $\Delta\nu$  and ping length  $\tau$ , it follows from Fourier analysis that for a suitably shaped pulse,

$$\Delta\nu = \frac{1}{\tau},$$

for  $\tau = 0.003$  sec,  $\Delta\nu = 333$  c. This is a minimum, and for a ping with a square envelope the required frequency spread is greater. Furthermore, allowance must be made for the doppler effect because of both the motion of the torpedo and that of the target. Since the band width of the receiver must be filled by the echo to utilize the discrimination against noise, the band width of the projector must cover this, in addition to the expected doppler displacement. For this reason, the radiated band width has been usually selected of the order of magnitude of 1,500 c.

Let  $L_t(\theta, R)$  be the spectrum level of the radiated signal at a distance  $R$  from the projector and off the axis by an angle  $\theta$ . It is assumed that the radiation pattern has circular symmetry so that  $\theta$  is the only angle on which it depends. It is also assumed that the intensity falls off with the square of the radius and with an attenuation factor  $\mu$ .

$$L_t(\theta, R) = L_t(\theta) - 20 \log R - \mu R \quad (1)$$

where  $L_t(\theta)$  is the effective level at 1-meter distance and  $R$  is the distance in meters. The attenuation factor is subject to variation over rather wide ranges under different oceanographic conditions. In addition, it increases with the frequency. In the neighborhood of 24 kc, 0.004 db per meter is a rough value for good sound conditions, while at about 60 kc it is near 0.014. If then  $\Delta\nu$  is the effective band width over which the energy may be assumed to be uniformly spread,

$$P = 2\pi \times 6.45 \times 10^{-9} \Delta\nu \int_0^\pi 10^{L_t(\theta)/10} \sin \theta d\theta. \quad (2)$$

The integral expresses the fact that the power is radiated in different directions and that the total power is the integral of the flow. The factor  $6.45 \times 10^{-9}$  converts the level based on a root-mean-square pressure of 1 dyne per sq cm to power in watts per square meter. The absorption between the projector and a distance of 1 meter is neglected. The integral can be expressed in terms of the directivity index  $D$  and the level for  $\theta = 0$  and  $R = 1$ ,  $L_t^\circ$ . Then it follows that

$$L_t^\circ = 10 \log P - D - 10 \log \Delta\nu + 70.9. \quad (3)$$

The level at any other angle can be obtained by subtracting the difference  $L_t^\circ - L_t(\theta)$ , obtained from the directional pattern.

In addition to the strength of the signal, the strength of the echo depends upon the nature of the target and the way it reflects the signal. For many purposes, the effective reflecting power of the target can well be expressed in terms of the radius,  $a$ , in meters, of an equivalent sphere, or the target strength

$$T = 20 \log \left( \frac{a}{2} \right). \quad (4)$$

This implies that the ship does not reflect like a plane but scatters energy in all directions, and serves as a satisfactory statement of the situation except when the torpedo is close to the target. A ship will have an effective target strength that depends strongly on its aspect. From ahead or astern the target strength will be much smaller than from abeam. Target strengths from zero to 25 db have been observed on surface ships.<sup>21</sup> For large submarines the target strength is about 25 db within 15 degrees of the beam. At other aspects it is rather variable because of the complicated shape of the submarine, but the values tend to fall around an average of 13 db.

The significance of the target strength is that, added to the signal level at the target, it gives the level of the reflected pulse at a distance of 1 meter from the target. The level of the echo at the projector is then obtained by subtracting another  $20 \log R + \mu R$ . Hence, if  $L_r^\circ$  is the reflected level,

$$L_r^\circ = 10 \log P - D - 10 \log \Delta\nu + 70.9 + T - 40 \log R - 2\mu R. \quad (5)$$

As was indicated in the section on torpedo self noise, the level of the reflected signal must be at least equal to the hydrophone response to the background and self noise. This sets an upper limit to the range that can be attained and a lower limit to the



power that must be used for a desired range. The question of reverberation is not involved in the determination of the necessary power, since the

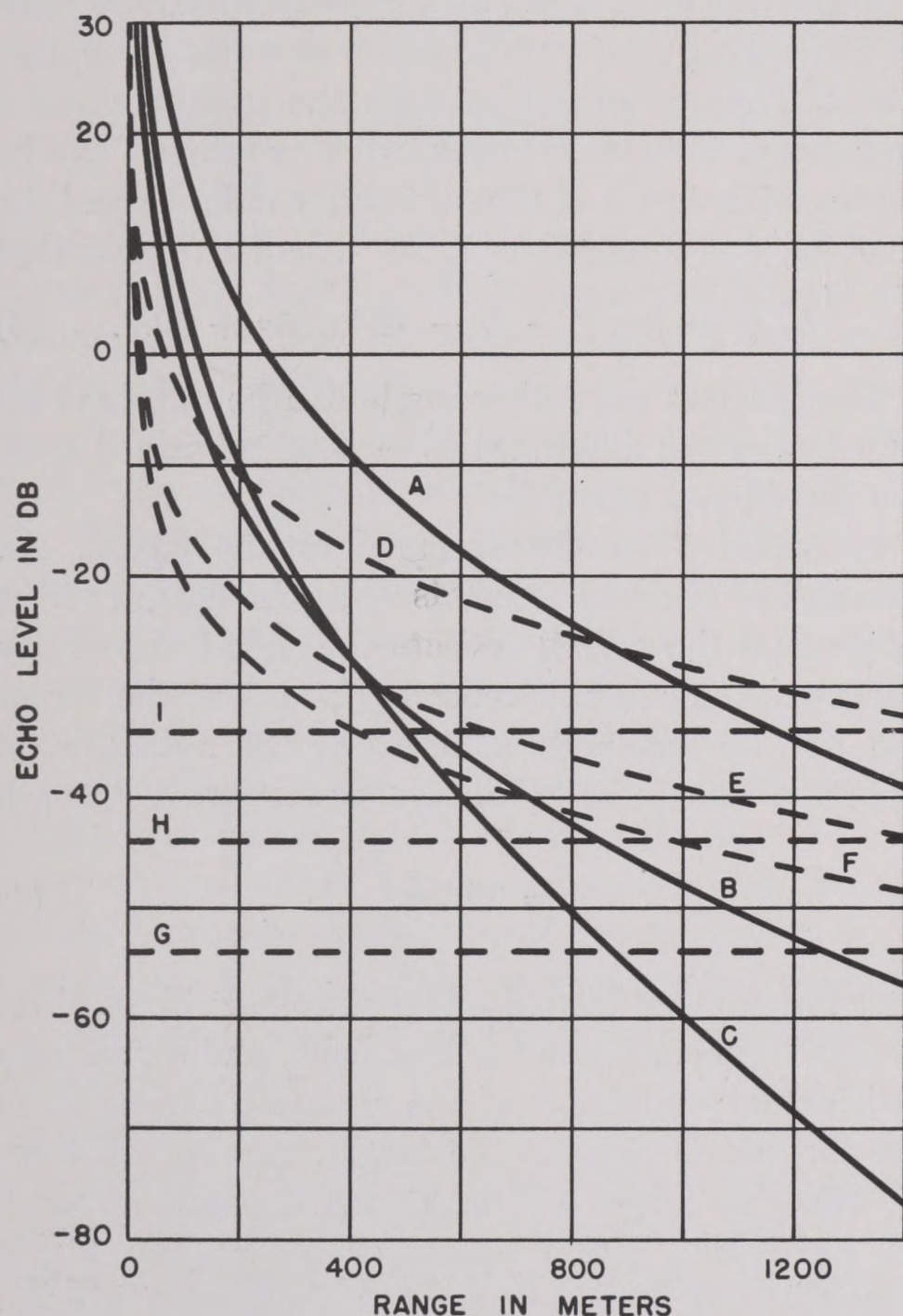


FIGURE 1. Curves A, B, and C represent the signal level reflected from a target of strength 10 db as a function of the range in meters. All three curves correspond to a frequency spread of 1,500 c. Curves A and B represent an absorption coefficient of 0.004 db per meter and curve C one of 0.028 db per meter. For curve A the power is taken as 1,000 watts and for curves B and C as 100 watts. The directive indexes for curves A and C are  $-19$  db and for B,  $-11$  db. Curves D, E, and F represent the noise level as a function of range from three types of ships, and curves G, H, and I represent three possible torpedo background noise levels.

reverberation is proportional to the power radiated.

In Figure 1 curves A, B, and C show the level of the returned echo as a function of the range of the target for a number of assumed conditions. Curve A represents more or less the situation contemplated

in a scheme for echo-ranging control of a large torpedo. The power  $P$  is 1,000 watts, the directive index  $D$  is taken as  $-19$  db, the frequency range as 1,500 c, the target strength 10 db, and the absorption coefficient  $\mu = 0.004$  db per meter corresponding to a frequency near 25 kc. Such a torpedo might have a self-noise level of at least  $-30$  db so that the maximum range to be expected would be in the neighborhood of 1,000 m.

Curve B represents somewhat the possibilities in the case of the proposed Bowler method of control. For illustration, the power is taken as 100 watts,  $D$  as  $-11$  db,  $\Delta\nu = 1,500$ ,  $T = 10$  db and  $\mu = 0.004$  db per meter. In this case the self noise may still be expected to be near  $-30$  db so that the maximum range might be near 450 yd.

Curve C corresponds to  $P = 100$  watts,  $D = -19$  db,  $\Delta\nu = 1,500$ ,  $T = 10$ , and  $\mu = 0.028$  db per meter. This is somewhat like the proposed ExFER42 mine control. The absorption coefficient corresponds roughly to what might be expected at 60 kc and, as can be seen from the curve, this is important at ranges over some 400 yd. For short ranges, and particularly for low frequencies, the absorption can usually be neglected.

The self-noise level of the ExFER42 mine at 60 kc is not well established but may be as low as  $-65$  db. Hence, the possible range is 1,100 m even with this rather low power.

In some cases the noise made by the target ship may be an effective part of the background noise and may tend to mask the echo. It may be possible to design the hydrophone and circuit so that the torpedo will steer on such noise, in which case the masking is unimportant. If, however, as is more usual, such a noise merely reduces the gain, it will be necessary for the echo level to be above the target noise as well as above the self noise. Figure 1 also shows curves D, E, and F of the expected target noise in several cases. From these it is clear that when the target noise exceeds the self noise of the torpedo, it is the target noise that sets the limit to the range that can be reached by echo ranging. Outside the useful range for listening, the echo-ranging system can be operated if enough power can be used.



## Chapter 12

# IDENTIFICATION OF THE ECHO

ONE OF THE major problems in the design of an echo-ranging type of homing control is to provide for suitable identification of the desired echo. The usual echo-ranging systems for locating submarines make extensive use of the skill of the operator in distinguishing the desired echo from all the other noises that are present. Such skill is usually developed only after long practice, and to make such distinctions automatically is quite a different matter. It is one of the major problems in the design of this form of homing device. After the signal is sent out, the listening hydrophone will hear a number of different types of noise in addition to the desired echo from the target. These may be listed as:

1. Self noise and background noise.
2. Noise originating at the target.
3. Reverberation.
4. Bottom and surface echoes as well as echoes from extraneous objects.

A number of schemes and devices have been suggested and discussed, and some of them have been tried, for distinguishing the desired echo from the other four types of noise. Several of these will be briefly indicated in this chapter and their performance with reference to the various interfering noises estimated. It is frequently possible to combine two or more of these schemes.

### 12.1 USE OF A SHORT SIGNAL

One method of identifying an echo is based on the use of a short pulse so that the returning echo constitutes a sudden and very short-lived increase in the intensity of the sound returning to the hydrophone. This method requires that the *automatic volume control* [AVC] in the detecting circuit have a long time constant so that the amplifier gain will not be changed by this very short pulse. On the other hand, it is also necessary that the steering circuit have a very short time constant in order to respond to this sharp peak. With this system, any sound that persists much longer than a pulse and for a long enough time to operate the AVC circuit merely causes a reduction in amplifier gain and does not affect the steering mechanism.

This system has some disadvantages with respect to discrimination against the self noise and background noise, since it may respond to sharp peaks in that noise because the time constant of the steering circuit is not long enough to smooth out these peaks. If, for instance, the self noise should be highly modulated, it might be necessary to set the amplifier gain so that the system would steer only on signals that are very much higher than the rms value of the background and self noise. The same thing is true with respect to noise originating at the target, so that such a system may have a disadvantage of as much as 6 to 10 db in its discrimination against noise originating at the target.

On the other hand, this system is particularly good for discrimination against reverberation. Since the intensity of reverberation is proportional to the length of the pulse emitted, the reverberation will be of a low level because of the use of a short pulse. In addition, in so far as the reverberation is not too irregular in form and does not contain too many peaks, the AVC circuit will reduce the gain so as to discriminate against it. Since bottom and surface echoes are roughly of the same nature as reverberation, the same statement applies to them. In general, it may be expected that a system using a very short pulse will not be limited by reverberation and bottom and surface echoes, but rather by self noise and noise originating at the target. The experience of the Bell Telephone Laboratories [BTL] in the application of echo-ranging homing and in the application of the Bowler scheme appears to bear out this expectation.

The advantages to be gained by this method are somewhat tempered, however, by the fact that the sharpness of the emitted signal tends to make the reverberation consist of many sharp peaks. The study of reverberation has shown this difference in character when produced by short signals as compared with the smoother form produced by a long drawn out ping. Furthermore, since the echo is not returned from a simple plane surface, it tends to be drawn out to some extent. If the reflection were produced along the whole length of a 300-ft ship, bow on, the echo would be drawn out to 120 msec. Nothing so extreme as this is likely to occur, but a



3-msec signal will be returned as an appreciably longer echo if the effective reflecting surfaces are distributed over 10 ft or more in range.

## 12.2 USE OF A LONG SIGNAL

In distinction to the system described above, one may undertake to make use of a relatively long pulse. The development of the ExFER42 mine by the General Electric Company and the Leeds and Northrup Company, Inc. has proceeded along this line. This involves the use of some type of volume control that will not operate on this pulse. In the case of the ExFER42 mine, the pulse is of the order of 30 msec in length, and it is then necessary either to have an AVC that does not operate on a pulse of this length or else to have some other form of gain control in the amplifier.

Because of the long time constants involved, this method may permit operation at only slightly above the rms value of the self noise and the background noise. Peaks in this noise will not affect the steering device at all. The same thing is true of noise originating at the target. On the other hand, because of the long pulse, the reverberation will be correspondingly high. Bottom and surface echoes will also be at a high level, since their intensity is similarly more or less proportional to the pulse length used. Hence one may predict that systems using this scheme will be limited by reverberation, including bottom and surface reverberation, rather than by self noise. The experience of the General Electric Company with the ExFER42 mine appears to bear out this prediction, although of course the self-noise level of the body with which they were working was very low.

## 12.3 THE USE OF A MODULATED SIGNAL

One method that has been suggested for distinguishing the echo from other noise is to impress on the outgoing signal a certain characteristic that can be recognized when the sound is returned as an echo. It is in this way that ordinary echoes are recognized in air when one recognizes a returning shout. The distinctive character of the sound may be in the form of simple modulation or it may involve frequency modulation. In fact, the two methods described above — that of a very short pulse and that of a very long pulse — may well be regarded as special cases of such modulation.

It is normally expected that the character of the echo will not be present in the self noise and background noise, since this noise is more or less random and if it has a modulation, the modulation of the signal can be selected to be distinctively different from it. The same thing is true, of course, of noise originating at the target except that its modulation may not be so well known in advance. Since the reverberation and the echoes from the bottom and surface are returned from a great number of different scatterers and different reflecting surfaces, the distinctive character of the pulse will be largely lost in them. On the other hand, it might be expected that the echo from a well-defined surface, such as that of a ship, might still contain a good deal of the character originally impressed upon the outgoing signal. This will probably be true to some extent, but, on the other hand, it must be remembered that the echo is not returned in general from a plane surface, especially in the case of a submarine. The echo is probably returned from a variety of different places on the submarine, so that the distinctive character of the signal will be preserved only in case it consists of modulation carried out so slowly that the change in character of the signal while passing over the target is not significant. Only a very small amount of experimental work on this point has been done in connection with homing devices. Somewhat more has been done with ordinary echo-ranging systems. It appears that the General Electric Company in their work on the ExFER42 mine have investigated a simple frequency sweep throughout their long pulse. They have not, however, used a detecting apparatus that was responsive only to a changing frequency.

## 12.4 USE OF THE DOPPLER EFFECT

Extensive experimental work has been done by the Harvard Underwater Sound Laboratory [HUSL] on the use of Doppler discrimination for identifying the desired echo. The signal returning from a reflecting surface will, in general, have a different frequency from that emitted because of the motion of the torpedo itself. This, however, is of little assistance because of the fact that there will be self noise and background noise as well as noise from the target at all frequencies, and, consequently, there will be interference at the frequency of the returned echo. Similarly, the reverberation and the bottom and surface echoes will be shifted in frequency from that



of the emitted pulse. If the target ship is at rest, the frequency of the echo will be shifted in the same way as that of the reverberation, but if the target ship is moving, the frequency shift will be different from that of reverberation and can be used as a means of separation. It has been possible to build a circuit that would recognize and operate only on echoes from a moving target. The presence of some reverberation can be used in order to determine the speed of the torpedo itself and the Doppler effect due to its own motion. It also requires that the beam used be not too wide, for otherwise the Doppler effect in the reverberation due to the sound sent directly ahead will be so different from that due to the sound emitted more to the side that the proper correction for the speed of the torpedo cannot be made. To make the most of this system a long pulse must be used. As indicated above, a long pulse permits the most satisfactory discrimination against the self noise. Since the Doppler effect is used to discriminate against the reverberation the long pulse must be used to reduce the significance of the other limiting factor.

The functional operation of such a scheme is moderately complicated, but can be made to operate more or less satisfactorily. It is, however, subject to the disadvantage that it cannot be made to operate against a stationary target. For details and discussion of this method, reference should be made to the work of the HUSL on Project NO-181.

## 12.5 SIMPLE TIME VARIABLE GAIN

To distinguish the echo from self noise and background noise on the basis of intensity, it is only necessary to require a signal somewhat higher than

the background noise to operate the steering system. If, however, it is required that a signal higher than the maximum of the reverberation is necessary for operation, the homing range will be almost infinitesimal because of the extreme change in level of the reverberation. At some time shortly after the signal is emitted, the reverberation will reach a maximum and then will fall off quite rapidly. In order to make use of signals of moderate level, it is necessary that the amplifier gain be increased as the reverberation decreases, but that the increase be stopped at such a point that the system will not steer on self noise. This can be done by means of an AVC with a suitable time constant.

For certain localities it may be possible to predict approximately the reverberation, and its rate of change, and to provide a simple change of the amplifier gain that will compensate for this assumed reverberation. If this can be done, one has a relatively simple system of identifying the echo merely by means of its intensity. This is generally done, however, at the sacrifice of a certain amount of possible homing range, because allowance must be made for the highest possible reverberation likely to be met.

The above has been a very brief discussion of some of the methods that may be used to distinguish the desired echo from the undesired noises. This is the basic problem of echo ranging, and in the application of echo ranging and homing control use must be made of all of the knowledge gained in the study of echo ranging or sonar systems. Although considerable attention has been given to the problem, and it appears that the ExFER42 mine will operate at least in a moderately satisfactory way, a great deal of study is necessary before the best possible method of operation can be selected.



## Chapter 13

### APPLICATION OF ECHO TO TORPEDO STEERING

**T**HE PROBLEMS OF maneuverability and stability on course are somewhat different in the case of torpedoes that home by echoranging than in the case of those that home by listening. This is because the echo information on which the steering is based comes only at intervals, and the intervals are longer the longer the contemplated homing range. For example, if signals are emitted every second, the maximum homing range is half the distance traveled by sound in a second, or roughly some 800 yd.

The above restriction assumes that time must be given for the echo to return before another pulse is emitted, and can be modified if two or more pulses of widely different frequencies are used in sequence. A period of 1 sec could be allowed for the return of each frequency, but the number of signals returning per second would be equal to the number of different frequencies used. Pushed to the limit this would result in an echo-ranging system similar to f-m sonar, and such a system might be useful in some cases. It seems questionable, however, whether such complication would ordinarily be justified. This is partly because the effective homing range that can be obtained with satisfactory reliability is perhaps not over 800 to 1,000 yd because of water conditions. When the ranges are limited to this amount, information can be obtained every second and this is probably sufficient for steering at a target whose maneuverability is similar to that of ships in use today.

While far from being a comprehensive study of the problem, three methods have been given a preliminary trial. All of these are subject to the restriction just discussed.

#### 13.1 THE BOWLER SCHEME

This is fundamentally the simplest method. It was suggested and started by the British, and was taken up and studied for a time by Bell Telephone Laboratories, Inc. [BTL].

The Bowler scheme is based on the idea of making the torpedo go into a circle when in the neighborhood of the target, and the echo-ranging system is used essentially to determine when the torpedo is in the

neighborhood of the target, and to which side of its first course it should circle. In the model later studied by BTL a hydrophone was placed on each side of the head of a Mark 13 torpedo. Sound pulses were emitted from both sides and the presence of an echo could be detected in one or the other hydrophone. In fact, the two sides are essentially independent. Each side is charged with the responsibility of determining if there is a target on its side. A satisfactory echo from one side puts the rudder hard over to that side and keeps it there so that the torpedo circles toward the target.

Preliminary analysis indicated that this simple scheme should very much increase the probability of an effective bow shot, while it would leave the probability of a hit from the beam essentially unchanged. It might, in fact, provide a target of roughly the same effective width from all directions. On the other hand it is clear that a homing range much greater than the turning radius of the torpedo cannot be used, and that both of these must be kept less than the length of the ship for a bow shot to be effective. The selection of the homing range and the turning radius must be made in the light of some knowledge of the length of the ship to be attacked, the relative speeds of torpedo and its target, and the relative importance of bow and stern shots.

In this system everything depends upon the proper identification of a single echo, for a false echo on the wrong side would turn the torpedo away from the target and it would never return. A false echo on the correct side might still cause the torpedo to turn toward the target, but to turn too soon and hence to miss. To minimize the possibility of steering on false echoes, it has been suggested that two or three successive echoes be required to put the rudder over.

With respect to steering problems this is perhaps the simplest possible system. It is subject, however, to all of the difficulties associated with identification of the echo that were described in the previous chapter; and this problem is of extreme importance for the reason just indicated. The difficulty is somewhat minimized, however, by the fact that only short homing ranges, of the order of 100 yd, are desired.



As a steering system the Bowler idea is unquestionably satisfactory, since a torpedo can easily be made to run in a circle at a set depth. It only remains to be determined whether the changeover from a straight course to a circle is an effective maneuver, and whether the echo-ranging system can identify the desired echo in order to make the switch with sufficient reliability and at the right time. Up to the present this has not been given any extensive field tests.

### 13.2 METHOD OF THE ExFER42 MINE

In the ExFER42 mine, steering and searching are combined in a simple and effective manner by giving the mine left rudder when no echo is identified and right rudder when an echo is heard. In practice this is made a trifle more complicated to minimize the effect of false echoes but the principle is as just stated. In the absence of an echo the mine turns steadily in a circle and searches for a target. When an echo is received and identified, the rudder is thrown right and held there until a certain period elapses during which no echo is heard. By this means the mine is made to approach the target along a sinuous path.

Here, as in the Bowler scheme, the rudder is thrown hard over and the mine goes into a circular path. It is important that the angular rate of turning be so related to the beamwidth of the projector and receiver that the beam does not sweep across the target before there is sufficient time to get a good echo.

Roughly, it may be said that the mine steers at one end of the target and the wake, since the wake is also a target which reflects the sound. As just described, the mine steers at the right end of the combination. If the normal direction of circling, without echo, is to the right, the mine will tend to steer at the left end. This may have some advantage in permitting the mine to follow along a wake until it comes to the target ship, unless of course it is going in the wrong direction. Preliminary field tests have shown that this system will operate satisfactorily against a submarine when it is combined with a suitable system for steering in depth. Presumably it will

also operate against a surface vessel but extensive tests on this point have not been carried out.

This introduces more dynamic problems than does the Bowler scheme because the torpedo is not allowed to settle down into a steady turning circle but may be barely out of the transient state before the rudder is reversed. In designing the system it is important to know the duration of this transient state. It is also important to minimize the roll both during the transient and the permanent state of turning. This is especially true if the projector is not symmetrical about the torpedo axis.

### 13.3 CORRECTION OF GYRO COURSE

The method that has been proposed by BTL for echo-ranging control of the Mark 14 and other torpedoes applies the acoustic information to the correction of the gyroscope heading. This can be done rather easily through the gyro preset mechanism, and the questions of stability on course are then merely those of the ordinary gyroscope steering.

In this system as experimentally built up, the receiving system determines the bearing of the target that returns the echo and turns the gyro to this bearing as long as it is less than some 6 or 7 degrees away from the torpedo axis. If, however, the target is farther than this from the torpedo axis, the gyro is turned only a maximum amount of some 6 or 7 degrees. This maximum angle is approximately the angle through which the torpedo itself can turn in the interval between successive echoes.

A similar method is used in the depth control of the ExFER42 mine. In this system the echo is interpreted as coming from either above or below the torpedo axis, and a pendulum that controls the rate of dive is adjusted accordingly.

Both of these applications make use of the information derived from the echo to make adjustments of the normal torpedo control mechanism. If these adjustments are made slowly enough, the dynamic properties and the stability of the control system are not affected. This is the occasion for the limited rate of turn indicated above in the Mark 14 experimental control. On the other hand, the adjustments must be made rapidly enough to provide the desired homing on the target.



## Chapter 14

### NEEDS FOR FURTHER STUDY

THE ABOVE OUTLINE indicates in a rough way the general state of knowledge concerning acoustic homing torpedoes. It is quite clear that the present knowledge of the subject is very sketchy, and is only barely sufficient to permit the construction of usable weapons. Many of the gaps in understanding have been quite apparent in the previous chapters but this chapter will constitute a brief summary of some of the principal lines along which additional research needs to be carried out.

#### 14.1 TACTICAL ANALYSIS

A good deal of study is needed to make clear what kinds of homing weapons are desirable and needed. It is easy to say that a homing torpedo should run as fast as possible, travel as far as possible, and should have as great a homing range as possible. In addition it should be as light as possible and carry as heavy an explosive charge as possible. It is obvious, however, that all of these ends cannot be accomplished at the same time. Some of them are more or less opposing, and it is important to make a careful evaluation of each one so that it can be properly appraised in reference to the others. Such a study would provide the basis for designing a suitable compromise.

A useful tactical analysis must be based on intelligent estimates of the objectives to be desired. It is probably not very practical to have a universal weapon which would naturally not be ideally adapted to any one purpose. A torpedo for use against merchant vessels may be quite different from one for use against naval vessels. The former may require only a slow running speed but possibly a long underwater range. It need have only a moderate explosive charge but may possibly require a long homing range. A torpedo for use against warships may require a much higher explosive charge, will certainly require a higher underwater running speed, and it may be proper to attain this latter by sacrificing homing range as well as underwater range. A torpedo to be launched from aircraft should probably have quite different specifications from one to be launched from submarines because the element of stealth is practically lacking from its tactical use.

Considerable attention also needs to be given to the subject of decoys. It seems probable that any acoustic homing torpedo is subject to a decoy of some kind, but careful analysis of the nature of possible decoys and their probable modes of operation can lead to a specification of a homing device of such a nature that the decoy problem is made as difficult as possible.

These tactical problems have already been given some attention,<sup>22</sup> and some tentative conclusions have been reached, but much more work on the problem is necessary before it can be considered as fully understood.

#### 14.2 SELF-NOISE STUDIES

The self-noise problem is really the heart of the acoustic homing torpedo problem. As has already been indicated, a great deal of work still remains to be done before the sources of noise are understood and before the best method of reducing and discriminating against this noise can be specified. The studies necessary in this connection can be grouped under several headings.

1. A thorough study of propeller cavitation is needed to determine if this source of noise can be eliminated while at the same time adequate thrust is maintained. Up to the present practically nothing has been put into practice along this line, and cavitation noise is reduced only by running the torpedoes at considerable depths. Against surface ships this makeshift involves all of the difficulties of acoustic steering in the vertical plane. These could be eliminated if quiet propellers were available.

Such a study will presumably require a carefully coordinated combination of theoretical and experimental work. This type of thing has been started by the Harvard Underwater Sound Laboratory, but it is a long-time program and it is probably only after several years of work that practical results can be expected.

Cavitation at other points on the torpedo must also be avoided but this is apparently not troublesome until speeds much higher than those at which the propeller cavitation now provides a dominant source of noise.



2. Attention is also needed to methods of reducing the machinery noise inside the torpedo and of the transmission of this noise to the shell. The sources of the noise are not at all clearly understood, and the methods of acoustically isolating the machinery from the shell have only been given very preliminary consideration.

3. The question of the dependence of self noise on frequency has not yet been given more than a very hasty examination. It is not known whether the use of higher frequencies would decrease or increase the difficulty due to cavitation noise nor how it would affect the problem of machinery noise.

4. A great deal of work is yet to be done on the problem of hydrophone isolation and the best way to provide a hydrophone that discriminates against the self noise of the torpedo. Presumably different characteristics are required to discriminate against cavitation and against machinery noise. Presumably the directivity pattern is of some importance, but the method of mounting is certainly of equal importance.

#### 14.3 HYDROPHONE STUDIES

In addition to the design of hydrophones to discriminate against self noise, considerable work seems

called for on the general subject of the proper kind of hydrophone to use under the severe conditions to which a torpedo is subject. Various types of crystal and magnetostriction hydrophones have been tried and suggested. Some of them have operated through the torpedo shell and some have required a hole cut in the shell. All of them are more subject to damage than would be desirable.

#### 14.4 ELECTRIC CIRCUIT AND CONTROL METHODS

The techniques available in electric circuits and electrical and mechanical methods of applying the acoustical information to the steering of the torpedo seem adequate to meet the requirements. Of course considerable work can be done to improve the reliability and simplicity of the whole system but it seems more important to determine what it is desired for the control system to do. This must be based on the kind of study included under tactical analysis.

Of course, additional study is always called for to improve methods of manufacture and maintenance, but the subjects just indicated seem to be those on which study is necessary to improve the functional performance of the homing torpedoes.







***PART II***

***ECHO-RANGING TORPEDO CONTROL SYSTEMS***

**SECRET**







## Chapter 15

### INTRODUCTION

**A**N ECHO-RANGING torpedo control system is one which employs a transmitter, operating at a definite frequency, which sends out an acoustic pulse into the water at periodic intervals and then controls on the echo, which is reflected back from the target.

Since the hydrophone in an echo-ranging control system is exposed to the self noise of the torpedo while it is listening for the returning echo, the response of the hydrophone to the self noise determines the lowest level of echo which can be effective in control of the torpedo. The following review of terminology and units should help the reader to follow later discussions of problems involving the use of transducers.

When a hydrophone is exposed to a pure-tone acoustic signal in water, a voltage is developed across its terminals because of the dynamic sound pressure on its surface. It is common practice in acoustics to express power and voltage ratios on a logarithmic scale. If there are two values of power,  $P_1$  and  $P_2$ , the result is by definition,

$$10 \log \frac{P_1}{P_2} = \text{power ratio}$$

expressed in decibels (db). If the two amounts of power are generated in systems of the same impedance, voltages will be developed such that the power is proportional to  $V^2$ . Then,

$$20 \log \frac{V_1}{V_2} = \text{corresponding voltage ratio in db.}$$

If  $V_2$  is 1 v,  $V_1$  can be expressed as  $20 \log V_1$  decibels relative to 1 v. The sensitivity of a hydrophone is normally expressed as the number of decibels relative to 1 volt per dyne per sq cm rms dynamic sound pressure when a pure-tone signal is used.

If the hydrophone is used to measure random noise in water, a reference pressure of 0.000204 dyne per sq cm is used, and the noise sensitivity of the hydrophone is expressed as the number of decibels relative to 1 volt per 0.000204 dyne per sq cm per c.

The intensity of a sound field is expressed in terms of the pressure generated in a hydrophone in a 1-c band width. Arbitrarily, a sound field is defined as zero spectrum level sound field when it is capable of

generating a dynamic sound pressure of 0.000204 dyne per sq cm in a band width of 1 c.

The intensity of the sound field is expressed in decibels spectrum (dbs) equals  $20 \log (\text{rms dynamic sound pressure per cycle}) / (0.000204 \text{ dyne per sq cm per c})$ . Since the power passing through unit area in the sound field is proportional to the square of the pressure, pressure ratios in the sound field can be expressed on a decibel scale as

$$\text{pressure ratio in db} = 20 \log \frac{P_1}{P_2}.$$

A zero spectrum level sound field therefore generates a pressure of 74 db below 1 dyne per sq cm per c.

If the band width to which a hydrophone and its associated equipment is sensitive is considered, the power absorbed by the hydrophone will be proportional to the band width in cycles per second. When two frequency ranges  $\Delta f_1$  and  $\Delta f_2$  are considered, the ratio of equivalent power expressed in decibels is

$$10 \log \frac{\Delta f_1}{\Delta f_2}.$$

The voltage generated in a hydrophone is equal to hydrophone sensitivity +  $20 \log p / 0.000204$  +  $10 \log (\text{band width in cycles per sec}) / (1 \text{ c})$ . The hydrophone sensitivity is the number of decibels relative to 1 volt generated by a sound field of zero spectrum level when the band width is 1 c. The rms sound pressure is  $p$  in the field in a 1-c band width and  $20 \log p / 0.000204$  is equal to the intensity of the sound field expressed in dbs.

As a practical example consider a noise field of 10 dbs which is being measured with a given transducer. Assuming that this signal is fed into two different receivers, one with a band width of 4 kc and the other with a band width of 1.4 kc, in the first case, that of the signal level as seen by the receiver of a 4-kc band width, the 10 dbs noise is 10 db above zero spectrum. The 4-kc band width is then 36 db above a 1-c band width and the effective dynamic sound pressure will be  $-74 + 10 + 36 = -28$  db below 1 dyne per sq cm. If the sensitivity of the transducer is 94 below 1 v per dyne per sq cm per c, the effective voltage developed by the transducer for



the 4-kc band-width receiver will be  $-28 - 94 = -122$  db below 1 volt. In the second case of the 1.4-kc band-width receiver, the effective dynamic sound pressure will be  $-74 + 10 + 31.5 = -32.5$  db below 1 dyne per sq cm and the effective voltage developed on the transducer will be  $-32.5 - 94 = -126.5$  db below 1 v.

Another important characteristic of a transducer is its directivity index. If a hydrophone is uniformly sensitive to sound incident from all directions, its directivity index expressed in decibels will be zero. If two hydrophones have the same sensitivity but different directivity index, they will give the same response to a unidirectional sound providing the sound arrives at both of the hydrophones on the axis of maximum sensitivity. If the hydrophones are placed in a sound field such as the ambient sound field in a body of water, where sound is incident uniformly from all directions, then the level of signal recorded by the two hydrophones will be different. For example, assume that two hydrophones, *A* and *B*, have the same sensitivity, but that *A* has a directivity index of  $-10$  db while *B* has a directivity index of  $-20$  db. Supposing that hydrophone *A* was used to measure ambient water noise with a given amplifier and then hydrophone *B* is substituted, the signal level observed with *B* will be  $10 - 20 = -10$  db, or 10 db lower than the signal observed with hydrophone *A*.

When a transducer is used as a projector it transforms electric energy from an alternating current into an alternating sound pressure; the relation between power and rms dynamic sound pressure is analogous to the familiar relationship connecting electric power, voltage, and resistance, and is given by

$$P = \frac{p^2 A}{\rho c}.$$

*P* is the power delivered measured in ergs per second, *p* is the rms dynamic sound pressure in dynes per square centimeter,  $\rho c$  is the radiation resistance where *c* is the velocity of sound measured in centimeters per second,  $\rho$  is the density of the medium in grams per cubic centimeter, *A* is the area of surface in square centimeters through which the sound passes. For example, if a projector of directivity index zero emits 400 watts of power into water, the rms pressure at 1 meter can be calculated from the preceding formula by use of the values

$$\begin{aligned} \rho c \text{ for water} &= 150,000 \text{ gm per sq cm per sec,} \\ A \text{ for 1-meter distance} &= 126,000 \text{ sq cm,} \end{aligned}$$

$$p^2 = \frac{150,000 P}{126,000} = 1.19 P.$$

Since

$$\begin{aligned} P &= 400 \text{ watts} = 40 \times 10^8 \text{ ergs per sec,} \\ p &= 40 \times 1.19 \times 10^4 = 6.9 \times 10^4 \text{ dynes per sq cm,} \\ 6.9 \times 10^4 \text{ dyne per sq cm} &= 97 \text{ db above 1 dyne per sq cm.} \end{aligned}$$

In case the directivity index of the transducer has the not unreasonable value of  $-23$  db, the rms sound pressure on the axis of the transducer at 1-meter distance will be

$$p = 97 + 23 = 120 \text{ db above 1 dyne per sq cm.}$$

If the sensitivity of a hydrophone is measured as a function of angle of incidence of the signal, the sensitivity normally varies in such a way that it reaches a maximum in one direction called the axis of the transducer. The curve showing the variation of sensitivity as a function of angle is called the pattern of the transducer. The directivity characteristics of the transducer are normally expressed in terms of the number of decibels reduction in sensitivity for a given angle measured from the axis. The curve of sensitivity as a function of angle usually shows secondary maxima of sensitivity at fairly large angles from the axis. These secondary maxima are called minor lobes and their sensitivity compared to the sensitivity on the axis of the transducer is an important consideration in the performance of the device.

An echo-controlled torpedo must be able to send out an acoustic signal, receive the echo reflected from a target, and on the basis of the information supplied by the echo, steer toward the target. The factors which influence the effectiveness of the echo are self noise of the torpedo, thermal gradients in the water, strength of the target, reverberation, and the use of countermeasures by the enemy.

The projector on the torpedo converts the electric energy generated in the transmitter into acoustic energy. The projectors normally used are designed with directive indexes of  $-20$  to  $-25$  db so that the acoustic energy is concentrated on the axis. As the sound progresses through the water it is reduced in intensity by the inverse square law and by absorption in the water. When it strikes the target a certain percentage is reflected back and on the return path the losses due to the inverse square law and water absorption again take place. In addition, thermal



gradients in the water can cause a further loss in the echo intensity.

During the period immediately following transmission of the acoustic pulse, reverberation is returned from the surrounding volume of the water and from the surface and bottom. This reverberation intensity decreases with time, and, although it is necessary to protect the receiver against it during the initial stages, it is not a factor which will affect maximum range.

In order to consider the problem exactly it is necessary to define a quantity called the target strength. Since it is possible to compute the reflectivity of a perfectly reflecting sphere, the equivalent sphere size is a convenient quantity to associate with a target.

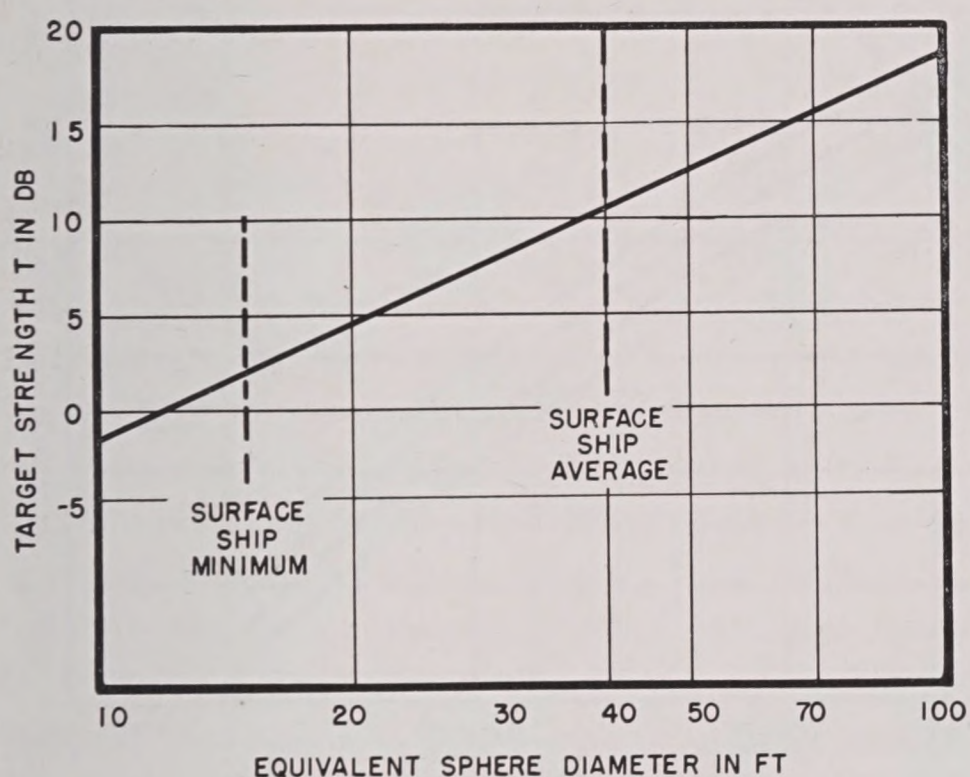


FIGURE 1. Relation between target strength and equivalent sphere size and representative target strengths.

If the transmission and reflection process are formulated more exactly, another more convenient means of expressing target strength can be derived.

Let  $L_0$  = rms pressure level of a transmitted pulse in db vs 1 dyne per sq cm at 1 yd from the projector in the direction of the acoustic axis;

$R$  = range in yards to the target;

$\alpha$  = attenuation in db per yard at the specified frequency.

The pulse intensity at the target may be expressed as

$$L_0 - 20 \log R - \alpha R$$

expressed in db vs 1 dyne per sq cm.

At the target, a certain fraction of the energy is reflected and the reflected ray suffers the same loss in returning to the target as it did in going out to the

target. The signal strength returned to the transducer will then be

$$L_0 - \underbrace{20 \log R - \alpha R}_{\text{Loss to target}} - \underbrace{20 \log R - \alpha R}_{\text{Loss from target}} + T.$$

In this expression  $T$  is the strength of the target in db necessary to make the above expression equal to the intensity of the returned echo.

It has been shown that

$$T = 20 \log D - 12$$

where  $D$  is the equivalent sphere diameter. A sphere of 4-yd diameter therefore has a strength  $T = 0$ .

Figure 1 shows values of  $T$  for several types of ships and it also shows the relation between target strength  $T$  and equivalent sphere size.

In order to utilize an echo for control of a torpedo it is necessary to have a small margin of signal level over the level of the self noise of the torpedo. It is possible to define the acoustic range of an echo-ranging torpedo by means of the following equation:

$$L_0 - 40 \log R - 2\alpha R + T = S + 10 \log W + M - 74$$

where  $L_0$  = the acoustic rms pressure level of the transmitted pulse in db vs 1 dyne per sq cm at 1 yd from the transducer on the acoustic axis;

$R$  = the acoustic range in yards;

$\alpha$  = the attenuation in db per yard;

$T$  = the target strength in db;

$S$  = the rms self-noise level in db spectrum (vs 0.000204 dyne per sq cm per c) as measured with the torpedo transducer used as a receiver;

$W$  = the band width of the system in cycles per second;

$M$  = the signal-to-noise margin in db required by the system.

If  $S$  is given in db vs 1 dyne per sq cm per c, the factor  $-74$  should be omitted.

Table 1 shows values of  $L_0$  for a series of values of acoustic power and for two values of directivity index.

TABLE 1

Acoustic power in watts	$L_0$ in db vs 1 dyne/cm <sup>2</sup> at 1 yd	
	For $D = -20$ db	For $D = -25$ db
250	115.5	120.5
500	118.5	123.5
1,000	121.5	126.5
2,000	124.5	129.5



Two commonly used frequencies for echo-ranging control are about 25 and 60 kc. The value of  $D$  for the 25-kc systems is approximately -20 db while for the 60-kc systems it is approximately 25 db. Making the assumptions indicated in Table 2 which are consistent with the best information available it

Present information indicates that the lowest feasible values for the torpedo self noise in a 30- to 35-knot torpedo are 15 to 20 dbs at 25 kc and 5 to 10 dbs at 60 kc.

Echo-ranging torpedo control has been used in all torpedo applications. The actual design of the con-

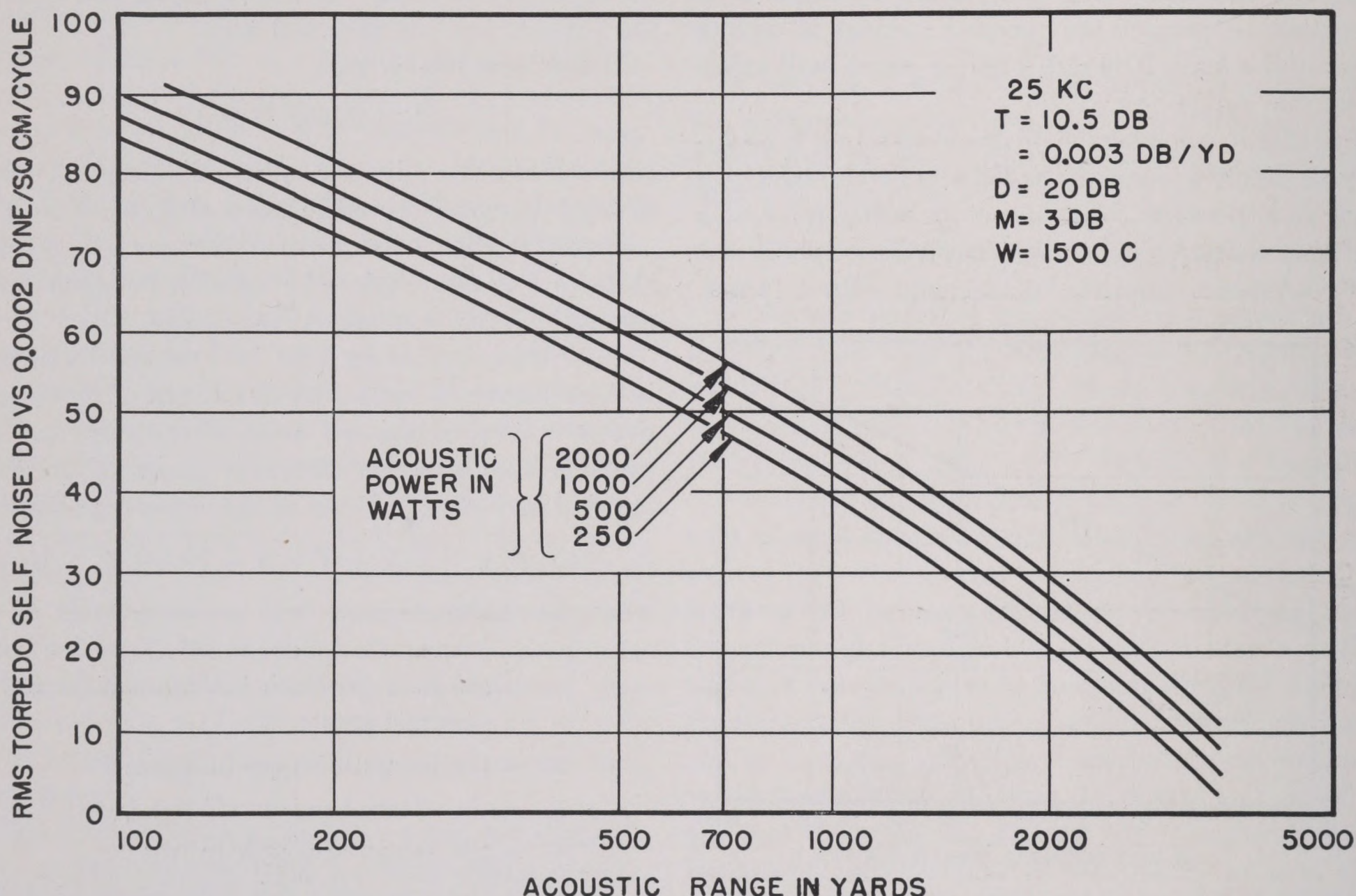


FIGURE 2. Acoustic range as a function of torpedo self noise at 25 kc.

is possible to calculate values of the maximum possible acoustic range as a function of torpedo self noise for different values of acoustic power output.

TABLE 2

Quantity	25 kc	60 kc
$\alpha$	0.003 db per yd	0.015 db per yd
T	10.5 db	10.5 db
W	1,500 c	1,500 c
M	3 db	3 db

Figures 2 and 3 show the maximum ranges calculated as a function of torpedo self noise for a series of acoustic powers for the 25-kc frequency and the 60-kc frequency.

It must be remembered that these are the values obtained under ideal operating conditions and will be decreased by the additional attenuation produced by thermal gradients if they are present.

control system, however, is determined to some extent by the application in which it is to be used. In anti-submarine applications, the torpedo is launched either from an aircraft or from a surface ship. When launched from an aircraft, the actual position and bearing of the submarine are not known. The torpedo is normally dropped as near as possible to the swirl left by the diving submarine. In this case the torpedo normally searches in a circle either at some fixed depth or with the depth continuously increasing. As soon as the torpedo receives an echo from the target it goes into acoustic control in both azimuth and depth until it either strikes the target or loses the acoustic contact. It is obviously necessary in this type of device to use acoustic control in both azimuth and depth.

In the case of a surface-ship-launched antisubmarine torpedo, there is some knowledge of the bear-



ing of the target at the time of launching, but the torpedo is launched at such short ranges that circling search is employed. Since the amount of explosive which is necessary to cripple a submerged submarine is less than that necessary to cripple a surface warship, a small torpedo is usually used in

limits the angle over which it is possible for the torpedo to locate a target in the initial search. Two compromises have been used. One is to make the beam pattern of the hydrophone very narrow in the vertical plane and broad enough to cover an angle of approximately 60 degrees in the horizontal plane.

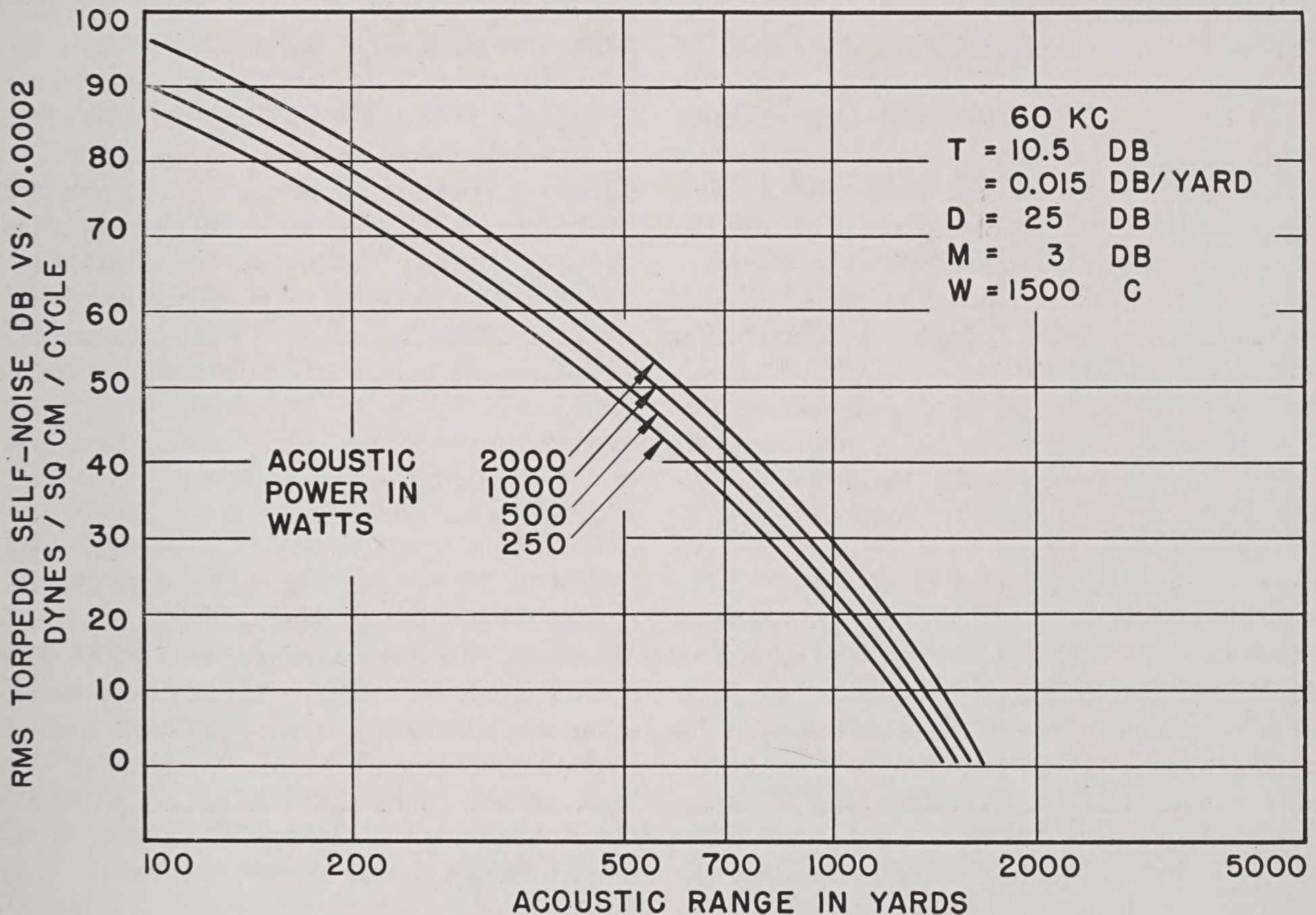


FIGURE 3. Acoustic range as a function of torpedo self noise at 60 kc.

this service. For tactical reasons, these torpedoes have been designed so that they can be carried in the bomb bays of ordinary bombing planes.

In anti surface-ship applications the torpedo may be launched from a submarine, from another surface ship, or from an aircraft. In these applications the bearing of the target is quite accurately known at the time of launching, and the range from which the torpedo may be fired is considerable. Since the operating range of these torpedoes is greater than their acoustic range, it is necessary to use gyro control in the initial portion of the run. From the standpoint of effects of self noise of the torpedo and the effectiveness of the countermeasures used against it, it is desirable to have hydrophones with quite sharp beam patterns. The effectiveness of the projector is also increased if its beam pattern is sharper. However, making hydrophone beam patterns very sharp

The other is to use a hydrophone with sharp beam pattern in both planes; but to control the gyro course so that, instead of running straight, the torpedo oscillates back and forth over the direction of firing so that its hydrophone can scan an angle of 60 to 80 degrees. Since the vertical level of a surface ship is fixed, anti surface-ship echo-ranging torpedo control systems are often arranged only for azimuth control and they depend on a purely hydrostatic control to determine the running depth. Since the self noise of a torpedo is determined largely by propeller cavitation, there is some advantage in operating at a depth of approximately 50 ft for the initial portion of an attack. In order to do this it is necessary to include means of acoustic control of depth in order to bring the torpedo up near enough to the surface to strike the target.

An echo-ranging torpedo control system is neces-

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sarily more complicated than a listening acoustic system. In order to justify the use of the more complicated system it must have sufficient advantage over the simple listening system. The echo-ranging device has the following advantages.

The countermeasures which are required to prevent it from striking a target are ordinarily different from those which are used against listening torpedoes. A properly placed noisemaker which simulates the noise of a ship is sufficient to limit the effectiveness of the listening device. Since it is possible to control the nature of the transmitted pulses in an echo-ranging system it is possible to predetermine the kind of countermeasure which will be necessary in order to limit its effectiveness. Variation of such things as the frequency of the acoustic signal, or the length of the transmitted pulse can be used to increase the difficulty in the use of countermeasures. One of the most effective means of countering an ordinary listening torpedo is for the target to slow down so that the noise generated by its propellers is much reduced. This procedure would be ineffective against an echo-ranging device. In the case of use as an antisubmarine device, echo-ranging torpedoes have been made to follow the wake of the submarine and make successful attacks from ranges even greater than possible acoustic ranges. Since the energy in the transmitted signal is concentrated at a single frequency, the frequency range of sensitivity in the receiver can be considerably less than that in the receiver of a listening torpedo. This means that the performance of the echo-ranging system will be less limited by the self noise of the torpedo than is the case in the listening devices. It is not possible to fire listening torpedoes in salvos because the later ones fired will tend to follow the earlier ones. By designing echo-ranging torpedoes so that more than one operating frequency is used, it is possible to fire successive echo-ranging torpedoes by using different torpedoes whose systems operate on different frequencies. If the echo-ranging system is so designed that it will not steer on noise, salvo firing can even be used with only one frequency of operation, providing the intervals of firing are great enough so that the sensitivity of the receivers of the later torpedoes will not be reduced because of the noise generated by the propellers of the first ones fired. A listening torpedo controls on the noise generated by the propellers of the target. The tendency is, therefore, for the torpedo to strike at or near the propellers, which will cripple the target but not necessarily sink it. On

the other hand, an echo-ranging torpedo tends to strike further toward the bow of the target and it is even possible to control to some extent the part of the target on which the torpedo will strike.

The use of an echo-ranging system also has some disadvantages. Perhaps the most important is the fact that its use gives it away. Very shortly after firing, the transmitter starts sending out acoustic pulses which can be received by the sound gear on the target. This makes possible the more effective timing of the use of countermeasures, and when the torpedo is fired from a submarine, it tends to give away the approximate bearing of the submarine at the time of firing. The greater complication in the control system necessary in order to utilize the maximum advantages of an echo-ranging system makes the maintenance and service problems with these torpedoes more difficult. The effectiveness of an echo-ranging control system also depends to a greater extent on external water conditions than is the case with a listening system. Since it is necessary for the acoustic signal to travel two ways instead of one, the conditions in the water unfavorable to the transmission of an acoustic signal will have a chance to operate on the echo-ranging signals twice. Layers causing refraction and reflection due to variations in salinity and temperature may sometimes cause considerable difficulty. Sometimes even masses of seaweed or schools of fish will behave as fictitious targets. In order to determine whether an echo-ranging system should be used rather than a simple listening system it is necessary to weigh these various advantages and disadvantages. The most effective arrangement is probably the use of both, with echo-ranging torpedoes to be used where the countermeasure problem is most important and listening torpedoes to be used where it is especially important to avoid detection of the submarine by the enemy. An acoustic torpedo provided with a switch on the outside of the body which could set it up either as a listening or an echo-ranging device, depending on the conditions existing at the time of launching, would be an ideal weapon.

In order to operate an echo-ranging torpedo, it is necessary to transmit pulses of signal at intervals, in order to provide periods in which the receiver can listen for the returning echo. Since sound has a velocity of about 5,000 fps in water, it is necessary to provide a listening interval of 1 sec for each 2,500 ft of range. If the maximum possible range of the torpedo is increased, the interval between transmitted



pulses must be increased in proportion. For this reason, the frequency with which information for acoustic control of the torpedo is received becomes less as the maximum range is increased.

The most common steering system used in torpedoes is the on-off type in which the rudder is turned either hard to port or starboard. If such an on-off steering system is used in a torpedo under echo-ranging control, the amplitude through which the torpedo will oscillate in the course of an attack will increase with the maximum acoustic range of the torpedo. If the transducers used have narrow beam patterns in azimuth, there is danger of information being received when the axis of the torpedo makes a considerable angle with the target bearing. It is necessary, for this reason, to consider very carefully the body dynamics of the torpedo and the sharpness of the beam pattern of the transducer in determining the maximum possible range which can be achieved using an on-off type of steering control. As the maximum ranges of echo-ranging torpedoes are increased, it will probably become more and more important to develop proportional types of steering control.

Assuming that the acoustic pulse which is transmitted into the water by a given transmitter and projector represents a given amount of acoustic power, the level of the echo returned by a target will be a function of the distance from the torpedo to the reflecting target. For greater distances between the torpedo and the target, the level of the echo will be less. Since the time of transit of the signal from the projector to the target and back to the hydrophone is a direct measure of the range of the target, it is possible to use a time variation in sensitivity of the receiver to take care of the variation in echo level with range. Another factor which makes this variation of receiver sensitivity with range important is reverberation. When the pulse of acoustic energy is transmitted into the water, a signal is received by the hydrophone because of the sound energy scattered back from the surrounding volume of water. This sound is known as volume reverberation. In addition to the volume reverberation, some sound is scattered from the surface of the water and also from the bottom of the ocean. These signals are known respectively as surface and bottom reverberation. Their importance relative to the volume reverberation is determined by the nearness of the surface and the bottom to the torpedo. In most cases the surface or bottom reverberation is the most important factor in the total reverberation level. The level of reverberation decreases with time after transmission in

much the same manner as the echo level from a given target. Use of time variation of sensitivity of the receiver can be used to prevent it effectively from causing the torpedo to steer on bursts of reverberation. This time variation in gain of the receiver amplifier can be controlled by the same time base which is used to control the time of transmission. This type of gain control is usually designated as TVG. In operating torpedoes under various conditions, the ambient noise which may be encountered in the water will vary from one place to another. The level of the ambient noise may be contributed to by noise-making countermeasures employed by the enemy. In order to protect the receiving system against such noise, the level of received signal may be used as a means of controlling the receiver sensitivity. In order to prevent the receiver sensitivity from being controlled by the level of the echoes, a large enough time constant must be used in the control network so that it will not respond during the interval of an echo. This type of control of receiver sensitivity is known as automatic volume control [AVC]. Most echo-ranging receiver systems employ both AVC and TVG, although, the manner in which they are actually employed varies considerably from one system to another. The time constant which is employed in the AVC loop will vary with the length of the transmitted pulse which is used.

An ordinary listening torpedo responds to the noise emitted by the propellers on the target, unless some sort of noise-making countermeasure is being used. An echo-ranging torpedo responds to the echo which is returned by the target; but, when the target is moving rapidly through the water, a wake is generated, consisting of large numbers of air bubbles which extends for a considerable distance aft of the target. The wake is an effective reflector, and the problem of devising a system which is capable of distinguishing between the wake and the true target is a difficult one.

One of the important advantages of an echo-ranging control system is the fact that one can increase the power of the transmitter to quite large values, and in this way control the level of echo returned by a given target at a given range. If the power of the transmitter is increased, the voltage required in the transmitter power supply is also increased. The development of suitable power supplies for use in the confined spaces of a torpedo presents some problems.<sup>a</sup>

<sup>a</sup> See references 1-8 and 41 for additional material on topics in this chapter.



## Chapter 16

### MAJOR COMPONENTS

**T**HE FOLLOWING major components are used in all echo-ranging torpedo control systems.

#### 16.1 TIME BASE

It is necessary in all echo-ranging systems to use a time base to determine the time interval between transmitted pulses and the length of the transmitted pulses. In addition, it is also necessary to make the receiver inoperative during the interval of transmission and, in cases where *time-varied gain* [TVG] is employed, to control the time of application of the TVG control voltage. The simplest form of time base is a system of cam-operated switches to control the various events. The cams may be operated by a simple motor drive or they may be operated directly by the torpedo propulsion motor. In some systems a purely electronic timing system is used, employing combinations of multivibrator circuits and relays. A system using an electronic time base has the advantage that the elements of the time base can be mounted directly on the chassis containing the rest of the electronic gear, whereas the systems using cam-operated switches have the advantage of simplicity and greater reliability.

#### 16.2 SIGNAL GENERATOR

The simplest type of signal generator which has been employed is the one used in the German Geier system, which consists of a condenser charged to a high potential and then discharged by means of a cam-operated switch through the tuned circuit of the transducer. The type of signal generator more commonly used employs either a power oscillator, which can be keyed by means of the time base, or an oscillator driving a power amplifier arranged so that both the oscillator and power amplifier are keyed by the time base. Since the signal generator is operating only a small fraction of the total elapsed time, the amount of power which can be generated during the actual transmitted pulse can greatly exceed the ratings of the components for continuous duty. The amount which these ratings can exceed the normal continuous duty ratings depends upon the length of pulse employed; for example, in the Ordnance Research

Laboratory [ORL] project 4 system the transmitter is capable of generating about 1.5 kw of electric power to be transmitted in 30-msec pulses, at 1.5-sec intervals. The power amplifier uses two 829B tubes with a plate voltage of 1,500 v. The Bell Telephone Laboratories [BTL] 157C system generates 1.5 kw of electric power in 3-msec pulses with one pulse per second, using a single 829B tube with a plate voltage of 3,000 v. It is impossible to use a plate voltage higher than 1,500 v with pulses as long as 30 msec with the 829B tubes, because the tendency for tube breakdown with excessive plate voltage is a function of the length of pulse. The power limitation in both of these systems is determined by the value of plate supply voltage at which breakdown begins to occur in the tubes rather than by the power-handling capabilities of the electrodes.

#### 16.3 TRANSDUCER

An important function in an echo-ranging system is the conversion of the electric power generated in the signal generator into acoustic power in the water during transmission, and then the conversion of the acoustic power in the returned echo into an electric signal which can be applied to the receiver. To do this, a single transducer may be used or separate units may be used as projectors and hydrophones.

When the same transducer is used for both projector and hydrophone, it is necessary to provide some means of protecting the receiver during transmission. This may be done by use of a switching system, combinations of varistors, or by special design of the coupling circuits to prevent excessive voltages being applied to the receiver.

#### 16.4 RECEIVER

The function of the receiver is to take the electric signal generated in the receiving hydrophone, amplify the signal, and use the information contained in the signal for the purpose of control of the torpedo. In all cases, the level of the receiver signal may vary from quite low values to quite high values depending on the range of the target. It is essential that the receiver be capable of handling the expected range of



signal level. This is usually provided for by the use of TVG and AVC. The receiver may be used to compare levels of signal on two separate hydrophones or the target bearing may be determined by the phase relation between the electric signals generated in the two halves of the receiving hydrophone. In the simplest case, the receiver may be made similar to those used in listening-type control systems; however, in order to best utilize the advantages of an echo-ranging system, the receivers usually contain means of processing the signal so that real echoes can be distinguished from other noises which may be present in the water. Since the transmitted pulse is a pure-tone signal, the range of frequency of signal to which the receiver must be sensitive is normally less than in the case of listening-type devices. It is, however, necessary to have sufficient range of frequency response to take care of the maximum amount of doppler shift in frequency which may be present in an echo. In some cases, the receiver contains two separate systems, one, a steering receiver, which interprets the signal to determine the direction of control necessary for the torpedo, the other, an enabling re-

ceiver, which determines, on the basis of the characteristics of the received signal, whether the steering receiver should pass its information on to the control system.

## 16.5

**RELAY CONTROL SYSTEM**

In order that the information which comes to the receiver be used for actual steering of a torpedo, it is necessary for this information to be passed on to the engines which control turning of the rudders. This is done by some sort of relay control system. In some cases only relatively rugged relays are used and sufficient amplification is used in order to operate these relays directly. In other systems, delicate relays are used to operate the rugged control relays and correspondingly less amplification is used in the electronic gear. In addition to the relays which are used for actual steering control, relays are also used to determine when the steering system should be locked off the normal gyro control; and in some cases where a special enabling receiver is used, the enabling of the steering receiver may be done by means of a relay.



## Chapter 17

### NATURE OF THE CONTROL PROBLEM

ECHO-RANGING torpedoes can be divided into two main classes: Those used in antisubmarine service and those used in anti surface-ship service. The torpedo used in the antisubmarine service is normally smaller than that used in anti surface-ship service, because the amount of explosive which is necessary to disable a submarine is less than that necessary to disable a surface ship. Most of the antisubmarine torpedoes are launched from aircraft and the use of a torpedo of about 7-ft length makes possible the use of standard bombing planes for launching.

The attacks made against submarines using acoustic torpedoes are usually made when the submarine is submerged. When the torpedo is launched from an aircraft, the location of the submarine is actually unknown both in depth and in position. It is therefore necessary, as was stated in Chapter 15, to have a torpedo which is capable of searching both in the azimuth and vertical planes. It is also necessary to have a torpedo which can operate at sufficient depth to attack a submarine at any feasible operating depth for the submarine.

When the torpedo is launched from an aircraft, it is normally launched at the point at which the submarine was seen to submerge. The torpedo is then expected to search until it makes acoustic contact with the submarine and then home on the submarine. If the torpedo is launched from a surface ship, the submarine will normally be located by means of the sound gear on board the ship so that the approximate bearing and range of the submarine are known at the time of launching. When the torpedo is launched from a surface ship, it is necessary that some means be provided in the torpedo to prevent it from homing on the launching ship. This is usually accomplished by means of a suitable ceiling switch and a means of providing for a certain search interval before acoustic homing can begin.

The method of azimuth search which is used in all echo-ranging antisubmarine torpedoes is to have the torpedo circle until it makes acoustic contact with the submarine. The depth behavior during search varies in the different systems. Some are arranged so that the torpedo dives fairly rapidly to some fixed

operating depth where it circles under hydrostatic control, whereas in others the torpedo dives slowly so that its search is a gradually descending helix. This dive may continue until acoustic contact is made or until the torpedo reaches bottom, or it may be interrupted at some predetermined depth and the torpedo level off.

In the actual acoustic control of an antisubmarine torpedo, it is necessary to control the device acoustically both in depth and azimuth. The method of acoustic control in the two planes may be the same. This is true in the system developed by the Harvard Underwater Sound Laboratory [HUSL] where the azimuth steering information is obtained by comparison of the electrical phase relation between the signal generated in the right and left halves of the transducer, and the vertical steering information is obtained by comparing the electrical phase relation between the signals generated in the top and bottom halves of the transducer. Somewhat the same procedure is used in a version of the British "Dealer" device, except that a switch is used in the time base which alternates the system from vertical information to azimuth information. In this way a single two-channel amplifier is used which alternately operates for azimuth and depth. The control for both azimuth and depth is accomplished by comparison of the phase of the electric signal generated in the two halves of the transducer. In the system which was developed by the General Electric Company, the method of securing acoustic-steering information in the two planes is different. In their system, comparison of the electrical phase relation between the top and bottom halves of the transducer is used for vertical steering control but the azimuth steering control is an on-off control. When echoes are received, the azimuth rudders are turned hard to starboard, whereas when no echoes are received, the rudders turn hard to port. By use of this arrangement, a single two-channel amplifier can be used for comparison of the phase of the signals for vertical control and the azimuth control is determined simply by whether the amplifier is receiving information or not.

In anti surface-ship service the torpedo may be



launched by aircraft, surface ships, or submarines. The problem of launching an acoustically controlled torpedo from a surface ship requires a definite precaution to prevent the torpedo from homing on the launching ship. In the anti surface-ship service the bearing and range of the target are fairly accurately known, and the range at which the torpedo is launched is normally quite large. All of the devices used in this service operate initially under gyro control. Provision is made for the torpedo, operating under gyro control, to get within acoustic range of the target and when acoustic signals are received, the acoustic control takes over. In the system developed by the Bell Telephone Laboratories [BTL], the acoustic control system acts by correcting the gyro setting so that the torpedo remains under gyro control during the whole period of an acoustic attack, the gyro setting being corrected on each received echo. The transducer used in this system has a fairly wide beam pattern in the azimuth plane so that it is able to receive echoes from any target within an angle of  $\pm 30$  degrees of the torpedo axis. The correction on the gyro setting is made by comparing the electrical phase relation between the signals generated in the two halves of the transducer when the echoes are received. In the German Geier system two sets of transducers are used which point respectively about 40 degrees to port and starboard of the torpedo axis. The system does not receive echoes from a point directly ahead of the torpedo and the torpedo remains on a straight gyro course until echoes from a target sufficiently off the axis to port or starboard are received. When an echo is received on either hydrophone, the steering system is locked off gyro control and the rudder is put hard to the side from which the echo is received. This condition is held until no further echoes are received, when the torpedo drops back on gyro control again. With this arrangement, if the original firing of the torpedo is sufficiently accurate to make a hit without acoustic control, the acoustic control system will not function. It simply functions to correct inaccuracies in the original gyro setting.

In the Ordnance Research Laboratory [ORL] project 4 system, a single very narrow beam-pattern transducer is used with its axis on the axis of the torpedo. In order to locate a target off the gyro course, the gyro is equipped with a special cam plate which causes the gyro course to be "snaky." The snaky course is such that the transducer is able to search over an angle of about  $\pm 40$  degrees. The use of the

snaky course reduces the forward rate of progress of the torpedo by about 5 per cent but it permits the use of a single transducer with a very sharp beam pattern, thus reducing the self-noise problem to a minimum.

In anti surface-ship service, it is not necessary to have acoustic control for the torpedo in both depth and azimuth. Most of the systems use only azimuth control, operating the torpedo at a running depth under hydrostatic control such that the torpedo will strike the target. Although the use of a vertical steering control makes the acoustic system more complicated, there is an advantage in operating the torpedo during the initial portion of the attack at a depth of approximately 50 ft, because propeller cavitation noise is reduced. This is especially important in the higher-speed torpedoes. It is conceivable that the vertical control might be accomplished by the use of two hydrostatic-controlled running depths, one used during search at the beginning of the acoustic attack and the other to be assumed after the attack has progressed for a certain length of time. However, this arrangement presents real difficulties, and the use of the acoustical information to control both the depth and azimuth steering seems to be the most desirable. The echo-ranging torpedo presents one definite advantage over the passive acoustic torpedoes in the operation of the depth-steering control, in that the echo-ranging system is itself a range-measuring device. One can introduce a range-measuring element in the time base which will permit depth steering only after the range has been reduced to a certain predetermined value.

In order to prevent the torpedo from oscillating through an excessive angle in the vertical portion of its attack, the vertical control should be introduced by the application of a correction on the normal hydrostatic control system. The simplest means of doing this is by application of a mechanical bias to the pendulum used in the hydrostatic control.

The normal torpedo steering control in the azimuth plane is one in which the rudder is thrown either hard to port or hard to starboard. A torpedo which is under gyro control normally requires the rudder to be thrown when the torpedo is a fraction of a degree off-course, resulting in a nearly straight trajectory for the torpedo. Under echo-ranging acoustic control, the angle off-course required to produce a rudder throw is greater than that necessary under gyro control and, in addition, an echo-ranging control system receives information intermittently. The

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time interval between successive echoes is a function of the acoustic range of the torpedo and may be considerably greater than 1 sec for long ranges. In the design of an echo-ranging system, it is necessary to take into account the acoustic range which is to be used and, therefore, the interval between transmitted pulses as well as the dynamic behavior of the torpedo body. The way these factors affect the reliability of the system will depend also on the sharpness of the beam pattern of the transducer and the actual method of acoustic control.

In the General Electric NO181 and in the German Geier devices, the azimuth steering is "on-off." Although there is actually considerable difference between these two arrangements, essentially the devices steer one way when echoes are not received and

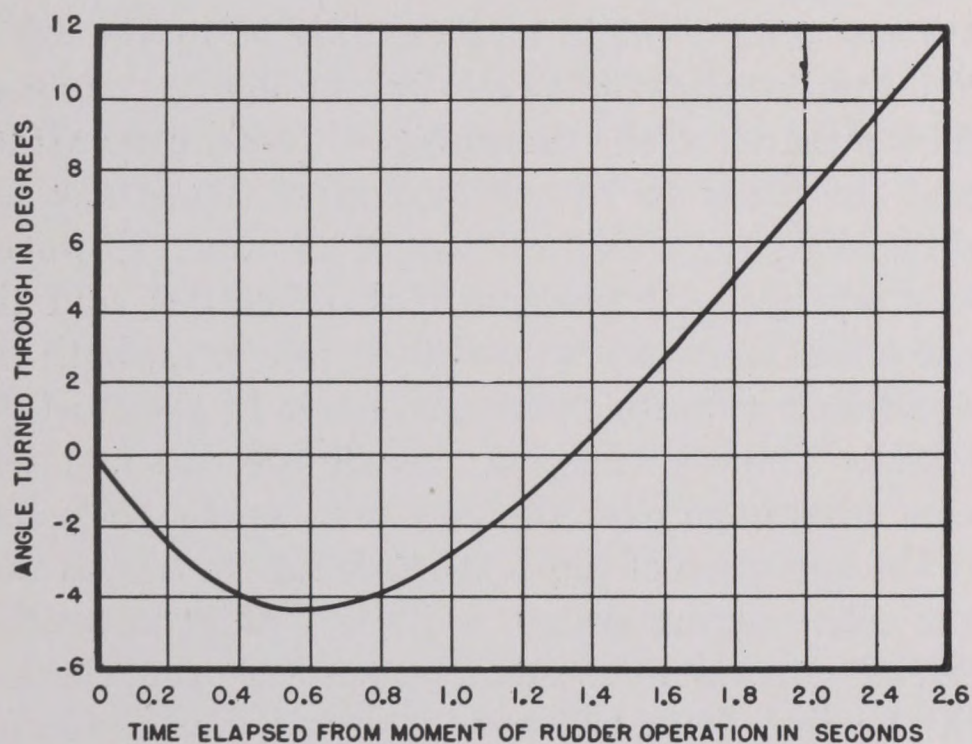


FIGURE 1. Orientation of body as a function of time following beginning of rudder throw.

the other way when echoes are received. It is necessary, with this arrangement, that the rate of turn of the torpedo be such that it is impossible for it to turn completely across the beam between echoes. For a given rate of turn of the torpedo body, the width of beam pattern required will be a function of the maximum acoustic range of the torpedo.

In systems like the HUSL NO181 and the BTL 157C, the steering is controlled by the electrical phase relation between the signals generated in the two halves of the receiving transducer. This means that it is necessary for an echo to be received in order to steer the torpedo in either direction. The transducer used in the BTL system has a very wide beam pattern in azimuth because the torpedo searches on a straight gyro course and utilizes the width of the beam pattern as its means of making initial acoustic

contact with the target. As soon as acoustic contact is made, the signal is used to correct the gyro setting. The dynamics of this body will therefore introduce no problem in maintaining acoustic contact with the target once acoustic contact is made. In the HUSL NO181 system, however, a transducer with very sharp beam pattern is used. The initial search in this device is circling and, as soon as acoustic contact is made, the rudders are held in either the port or star-board position depending on the phase relation of the signal generated in the transducer by the last received echo. The dynamics of the torpedo body are quite important in this device. The ping interval used is 0.65 sec, the rate of turn of the body is 12 degrees per sec, and an interval of 1 sec is required for the rudders to turn from one extreme limit to the other because the steering is done by means of an electric motor. The effect of the dynamics of this body on the relative sensitivity of the acoustic system can be determined by considering the solution of equation (1)

$$Q \frac{d^2\theta}{dt^2} + R \frac{d\theta}{dt} = L(t). \quad (1)$$

This is the equation of motion of such a body under the influence of the torque introduced by the rudder.  $Q$  is the moment inertia of the body.  $R$  is the angular

TABLE 1

Echo no.	Angle (degrees)	Rel. sig. 130 yd (db)	Rel. sig. 260 yd (db)	Rel. sig. 520 yd (db)
1	- 8.8	- 9.1*	- 7.5*	- 5.6*
2	-15.1	-30.9	-29.3	-23.3
3	-14.3	-34.0	-35.0	-33.7
4	- 8.8	-13.5	-15.9	-21.6
5	- 1.5	- 1.0	- 2.2	- 5.6
6	+ 6.3	- 4.6*	- 3.5*	- 3.2*
7	+12.6	-23.0	-19.3	-15.0
8	+11.8	-22.4	-23.4	-22.2
9	+ 6.3	- 7.6	- 9.4	-13.5
10	- 0.9	0.0	- 0.5	- 3.1

\* Steering must take place.

damping resistance,  $L(t)$  is the rudder torque as a function of time and  $\theta$  is the spacial orientation of the body axis.  $Q/R$  is called the relaxation time of the body, which is the time, measured from the time of rudder throw, necessary for the body to come back to the same spacial orientation which it had at the time of rudder throw.  $L/R$  is the rate of turn of the body measured in degrees per second. The HUSL

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NO181 body had a value of relaxation time of 0.5 sec and the rate of turn was 12 degrees per sec.

TABLE 2

Echo no.	Angle (degrees)	Rel. sig. 130 yd (db)	Rel. sig. 260 yd (db)	Rel. sig. 520 yd (db)
1	-3.6	- 1.0*	- 1.0*	- 2.0*
2	-9.9	-13.8	-11.2	- 8.3
3	-9.1	-13.4	-14.1	-13.3
4	-3.6	- 3.0	- 4.3	- 7.0
5	+3.6	- 1.0*	- 1.0	- 2.0
6	+9.9	-13.8	-11.2	- 8.3
7	+9.1	-13.4	-14.1	-13.3
8	+3.6	- 3.0	- 4.3	- 7.0

\* Steering must take place.

The curve in Figure 1 shows the orientation of the body as a function of time following the beginning of the rudder throw. The data below show the relative level of the received signal at 130 yd, 260 yd, and 520 yd for the most favorable and the most unfavorable

phase relation between body orientation and transmission of the pulses. Table 1 is for the most unfavorable condition and Table 2 is for the most favorable condition.

It is obvious that in order to receive every echo, the echo-to-reverberation ratio would have to be extremely high. Actually it is not necessary to receive every echo since the steering system holds in the position of the last steering indication. It is therefore necessary to have only about 11 db echo-to-reverberation ratio to steer in the worst case considered in Table 1 and 8 db ratio to steer in the worst case in Table 2.

When the steering in the vertical plane is accomplished by the same type of hunt as is used in the azimuth plane, the condition for combined steering in both planes can be considerably worse than that for one plane. The use of glide-angle control in the vertical plane makes the effect of the dynamics of the body on acoustic performance much less serious.



## Chapter 18

### GENERAL ELECTRIC NO181 SYSTEM

#### 18.1

#### INTRODUCTION

IN 1942 a research group of the General Electric Company started development of an echo-ranging control system to be used in an antisubmarine torpedo. The system was designed as a conversion system for a torpedo which was already in use as an antisubmarine listening torpedo. In August 1944, their experimental units were tested and the device was accepted by the Navy for production. The production engineering was undertaken by the Leeds and Northrup Company, and their first preproduction units were tested during the summer of 1945.

no provision for *automatic volume control* [AVC]. The device is protected against steering on noise peaks by the use of an amplitude gate with a time constant which requires a substantial part of the 30-msec pulse to enable. The pulse interval of 0.7 sec makes the maximum theoretical range about 560 yd, but performance tests on the preproduction models have all been made at 330 yd. The device is intended to be dropped from an aircraft at the point where a submarine has submerged. It searches in a circle with the depth gradually increasing until acoustic contact is made. It then homes on the target.

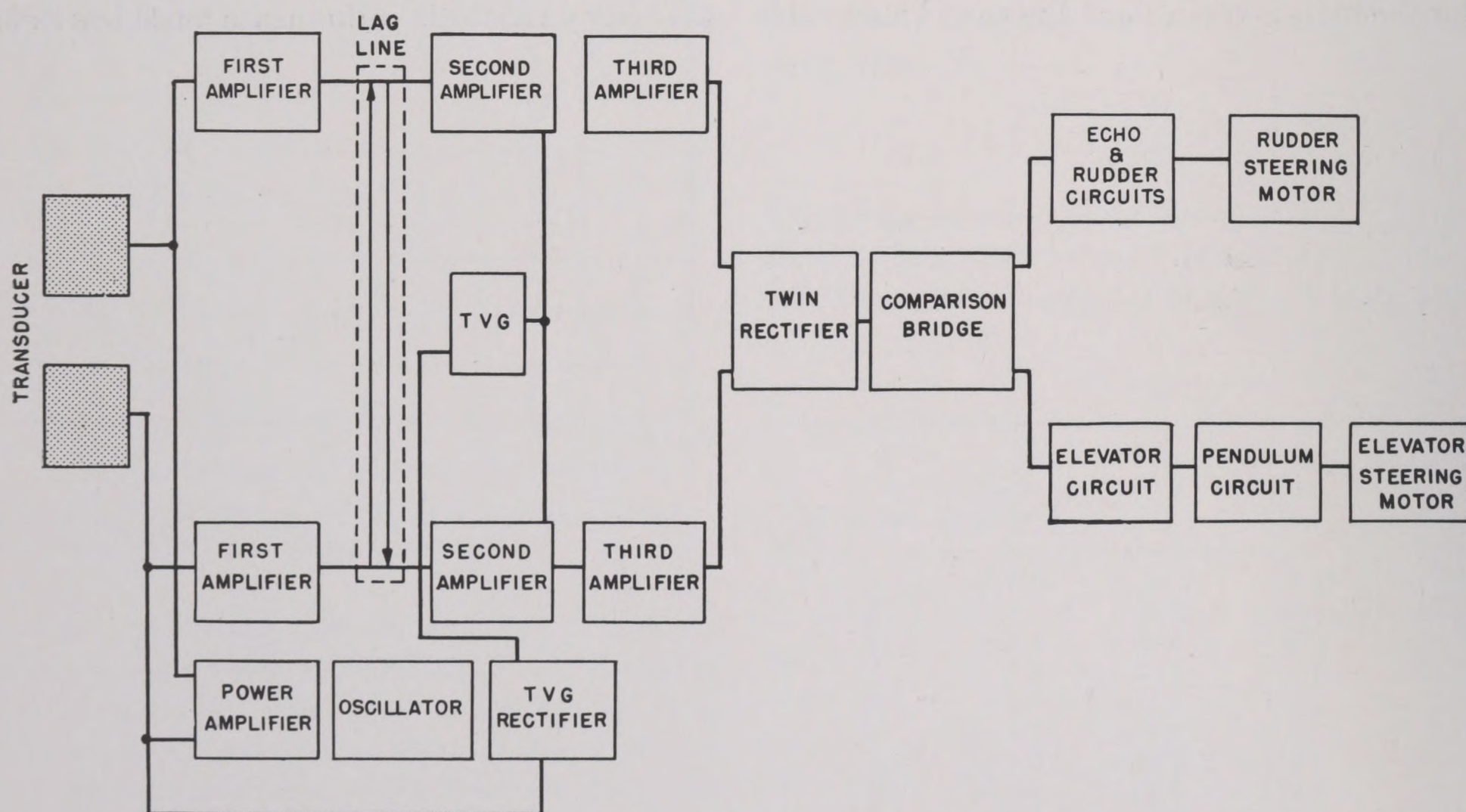


FIGURE 1. Block diagram of General Electric NO181.

Figure 1 shows a block diagram of the system. It consists of a transmitter capable of generating about 100 watts of electric power to be transmitted in 30-msec pulses at 0.7-sec intervals. A single transducer is used as both projector and hydrophone. The receiver contains two types of steering-control systems, one for the azimuth control and the other for depth control. The operating frequency is 60 kc. The receiver is under *time-varied gain* [TVG] control with

#### 18.2

#### TRANSDUCER

The transducer used in this device was developed at the Harvard Underwater Sound Laboratory [HUSL] and consists of an array of magnetostrictive elements. Figure 2 shows the general construction of the transducer and the individual elements, while Figure 3 shows the arrangement of the elements in the array. The numbers indicated on each element



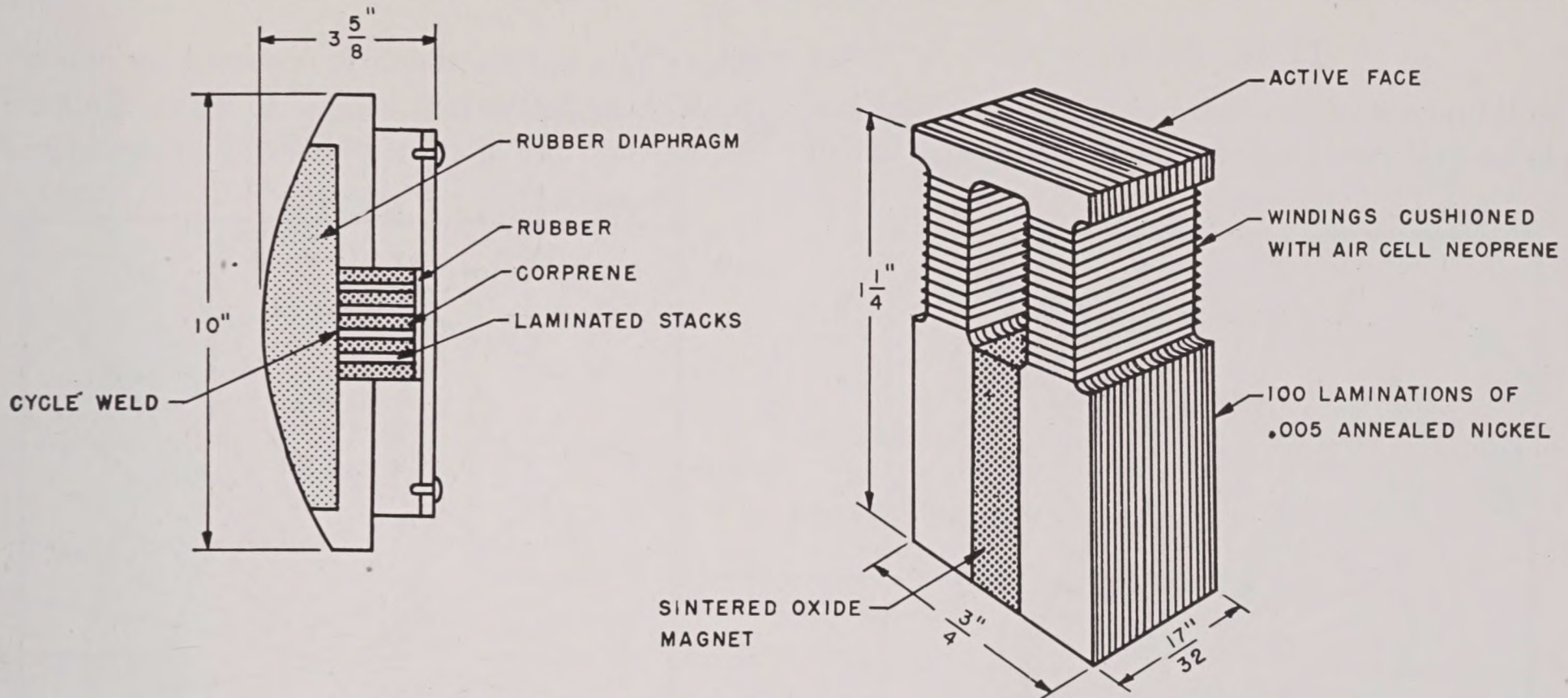


FIGURE 2. Details of transducer construction.

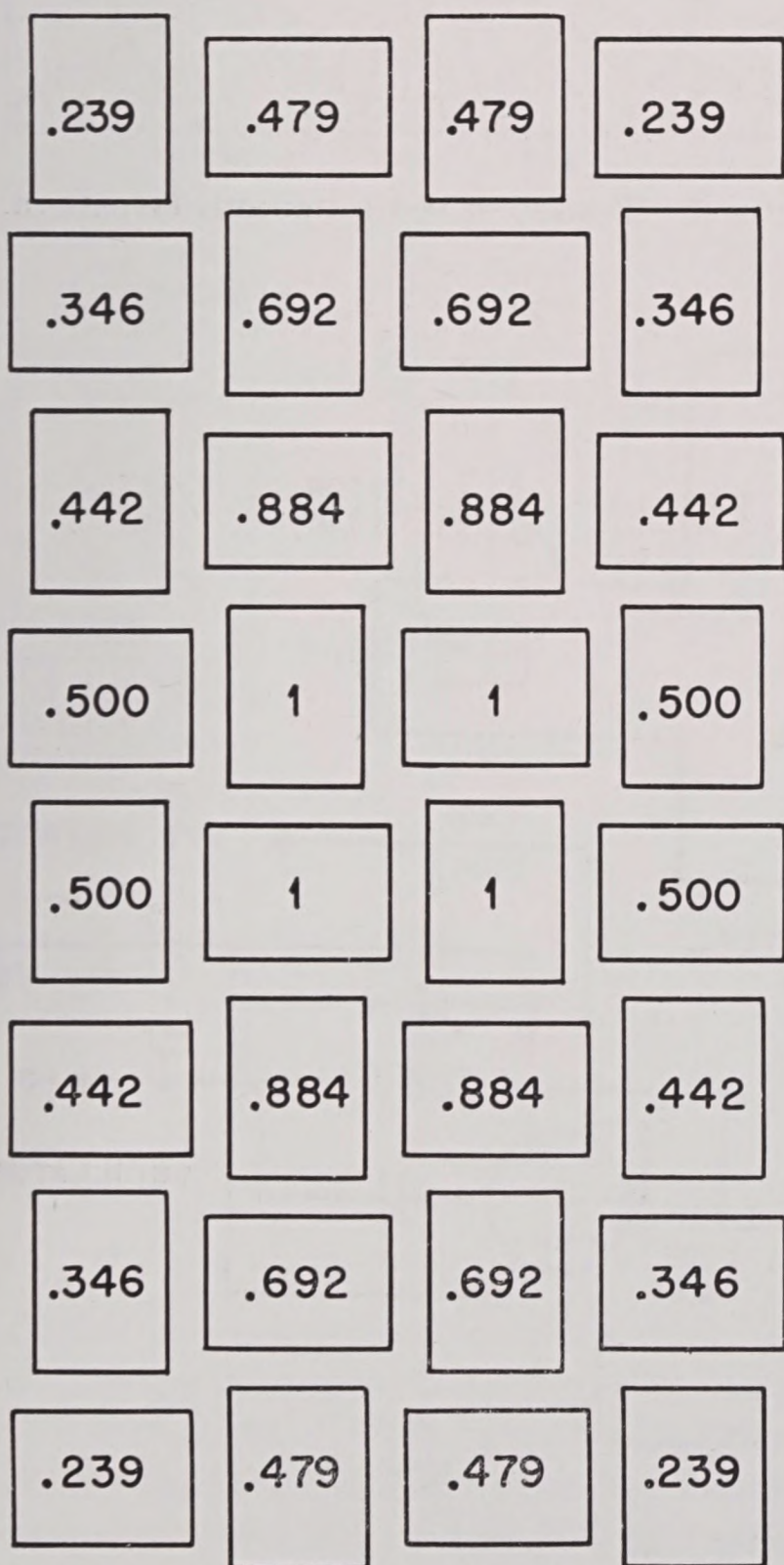


FIGURE 3. Array of elements in the transducer.

units is for the purpose of controlling the pattern of the transducer. Figure 4 shows the frequency response curve of one of the transducers produced by the Leeds and Northrup Company, Figure 5 shows the horizontal pattern, and Figure 6 shows the vertical pattern. The following are the numerical characteristics of a representative transducer: In the vertical plane, the pattern is 10 db down at 10 degrees off the axis on either side, while in the horizontal plane the pattern is 7 db down at 10 degrees off

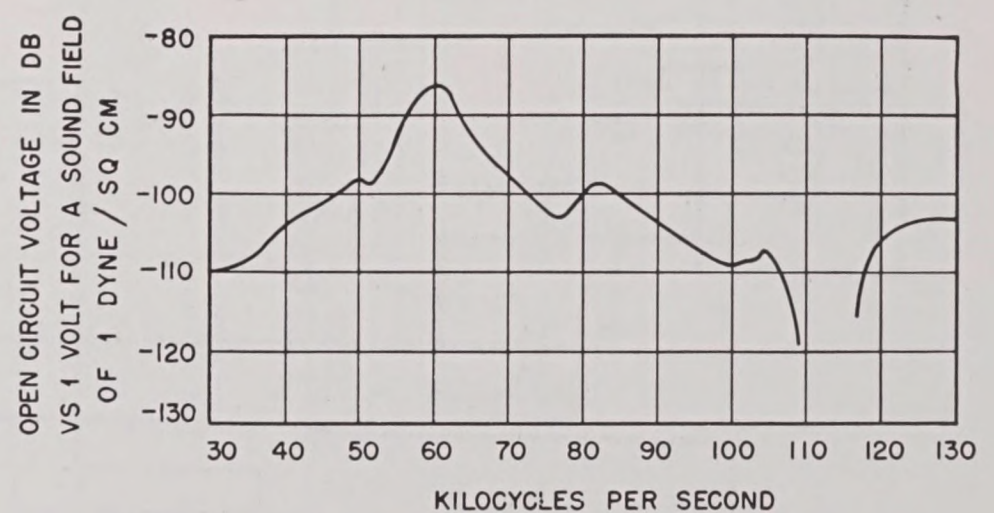


FIGURE 4. Transducer frequency response.

the axis and the overall directivity index is - 22.5 db. In the process of adapting the transducer to production, the impedance per unit was changed somewhat so that the impedance per half section comes out  $90 + j130$  ohms. The receiving sensitivity is 82 db below 1 v per dyne per sq cm and, during transmission, 66 db above 1 v per dyne per sq cm is developed at a range of 1 meter. The efficiency in transmission is about 35 per cent and, it is believed by the Leeds and Northrup people that the latest units which they have produced are somewhat better than this.

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in this figure indicate the relative number of turns in the windings. The variation in the windings on the



## 18.3

## TIME BASE

The time base of the General Electric system is a simple cam-operated set of switches. The cams which

means of a switch which is operated by one of the cams. A second switch is used to blank the receiver during the time of transmission by applying  $-26$  v

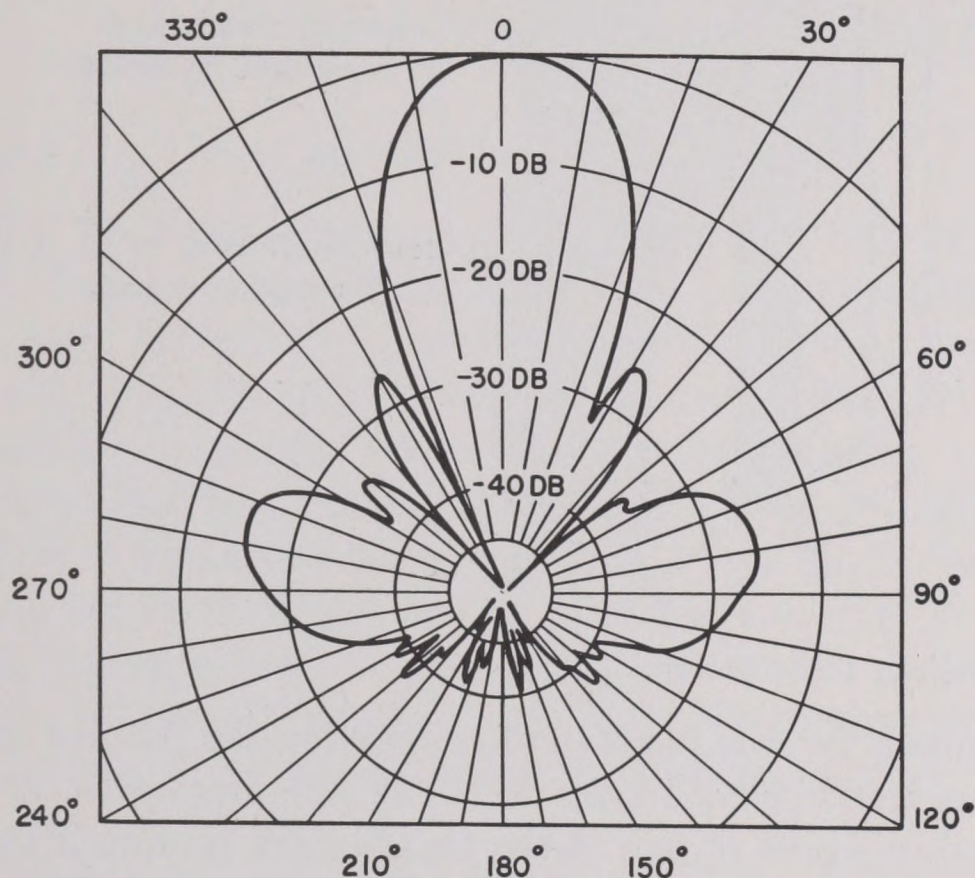


FIGURE 5. Transducer horizontal directivity pattern.

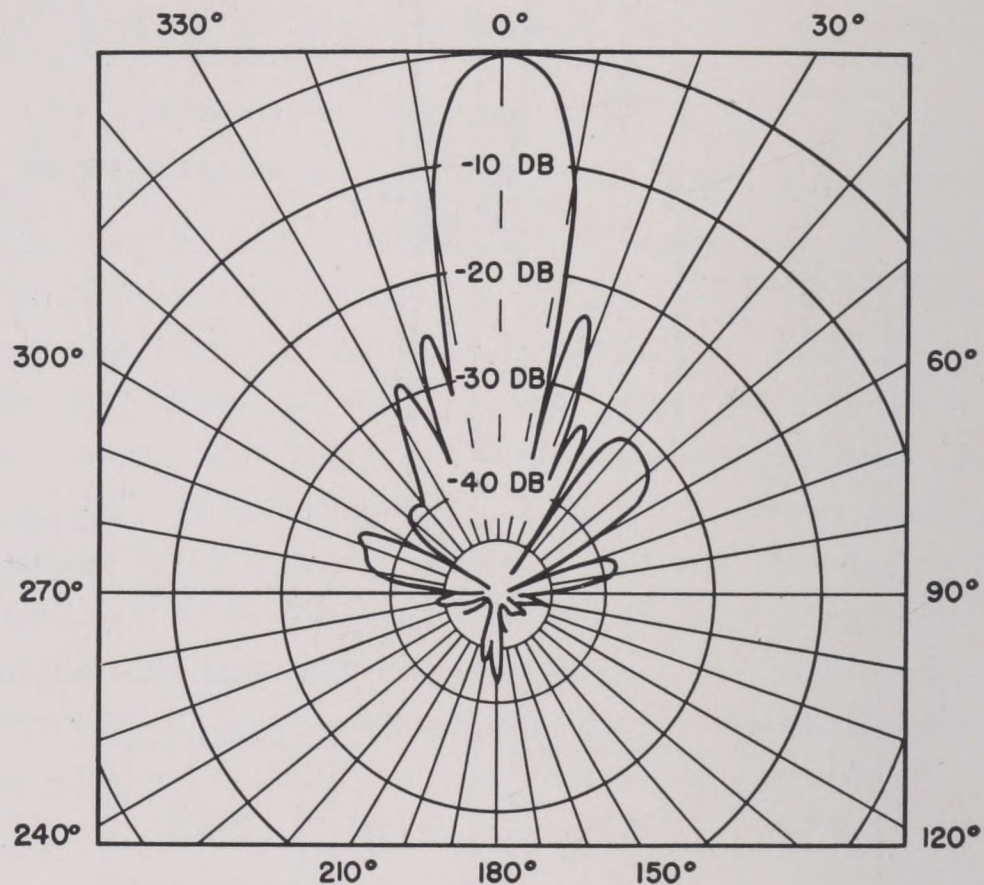


FIGURE 6. Transducer vertical directivity pattern.

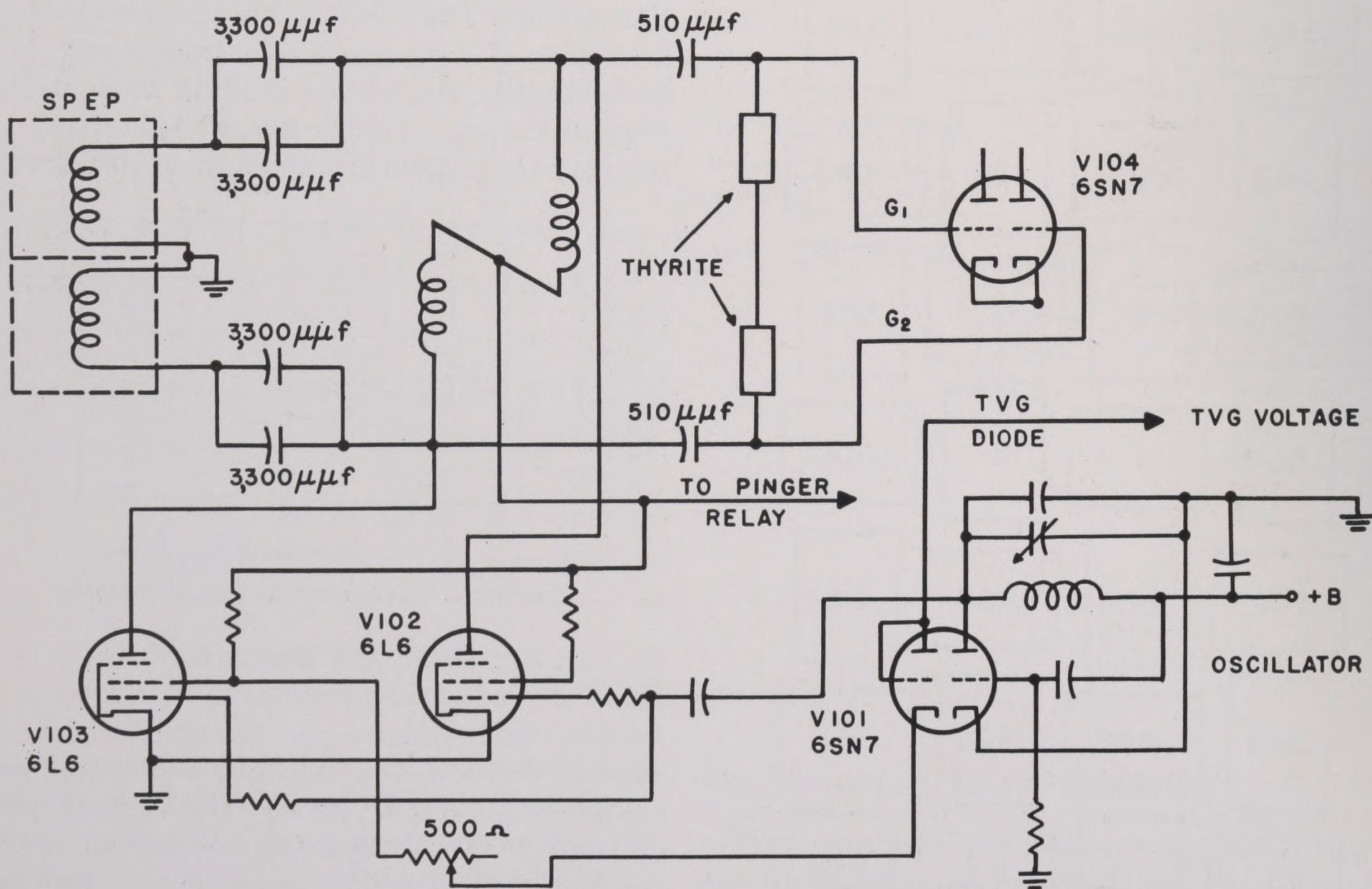


FIGURE 7. Transmitter.

operate the switches are on a shaft which is driven by the main motor shaft. The transmitter is operated by keying the plate supply of the signal generator by

directly to the screens of the tubes in the receiver. Three other cam-operated switches are used to control the range of the torpedo. The first is a single-

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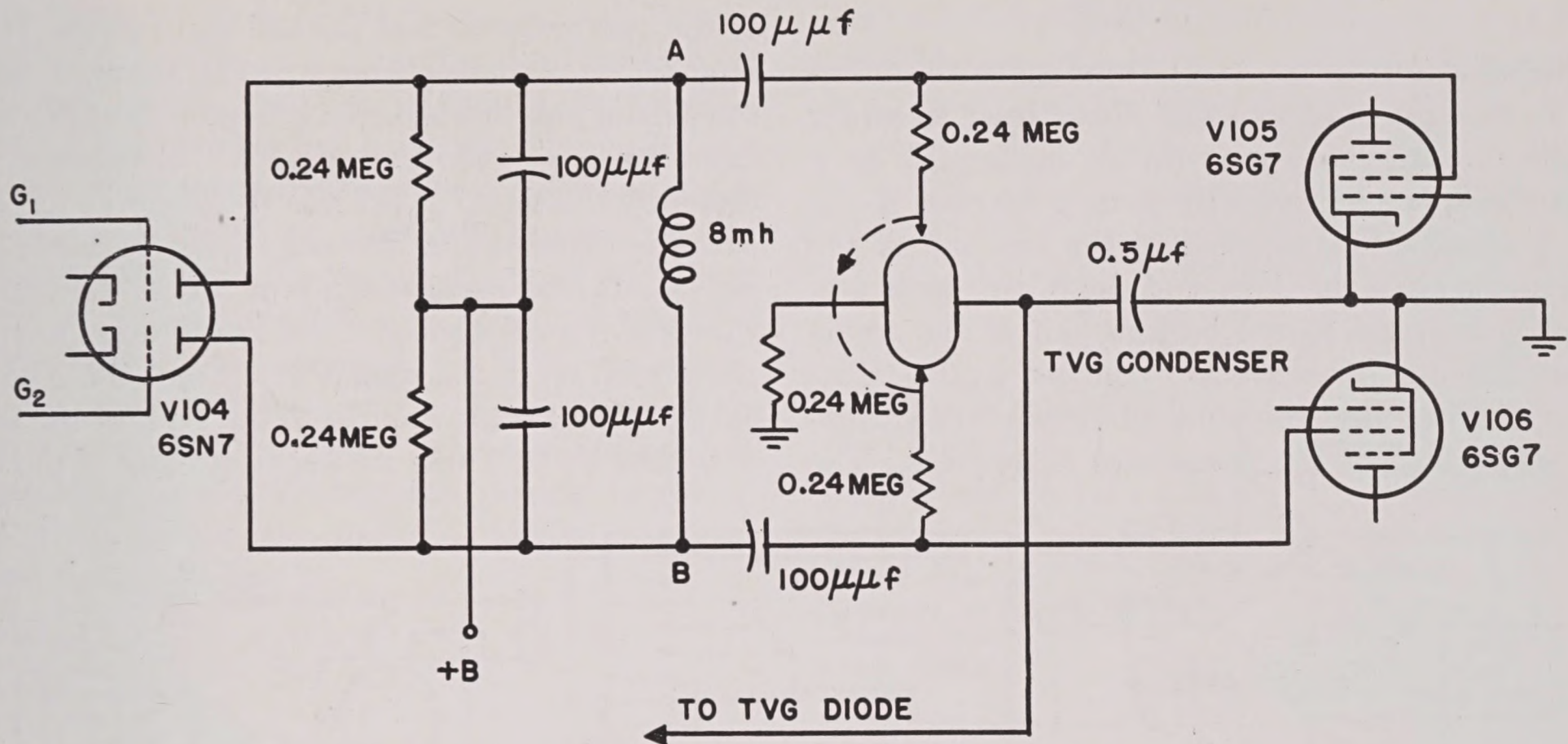


FIGURE 8. Lag line and TVG balance control.

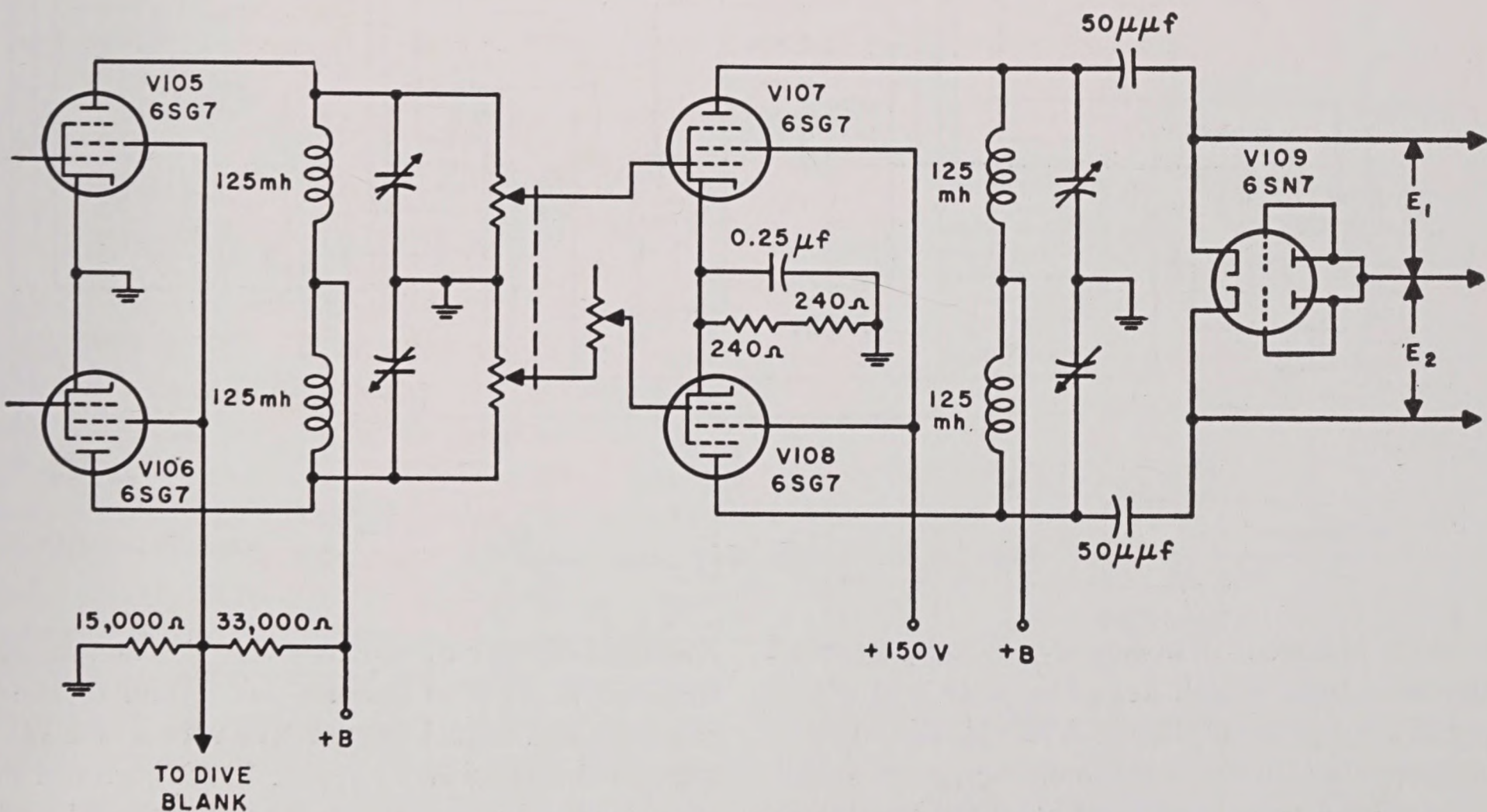


FIGURE 9. R-F amplifier and rectifier.

pole double-throw switch which is closed in one position during the time that echoes can be received from ranges less than 500 ft. It is closed in the other position during the time that echoes can be received from ranges greater than 500 ft. This is used to limit the range to 500 ft after echoes have once been received within this range. The second is closed by a cam during the time that echoes can be received from ranges between 1,000 and 2,000 ft, and the third is closed

during the time that echoes can be received from ranges between 1,500 and 2,000 ft. By means of these last two switches, it is possible to decrease the range of the torpedo to 1,000 ft, if the body is tilted so that it points toward the bottom at an angle greater than 9 degrees and to 1,500 ft, if the body is tilted so that it points toward the bottom at an angle greater than 6 degrees.

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## 18.4

## TRANSMITTER

The schematic of the transmitter is shown in Figure 7. It consists of two 6L6 tubes used as power amplifiers with their grids driven in parallel by a single 60-kc oscillator. The output of one of the power amplifiers is supplied to the top half of the transducer while the output of the other power amplifier is supplied to the bottom half of the transducer. The amplifiers are so connected to the transducer windings that the acoustic signal emitted from the whole face of the transducer is in phase. The

at the two grids G1 and G2 will be in phase. If the acoustic signal comes from a point above or below the axis of the torpedo, the phase of the signals on the two halves of the transducer will be different and therefore the signal at G1 will no longer be in phase with the signal at G2. Because of the presence of the lag line in the plate circuits of V104, the relative values of the voltages at A and B will depend on the phase relation of the signals at G1 and G2. The signals at A and B are applied to the grids of the tubes V105 and V106. These are the first stages of the two-

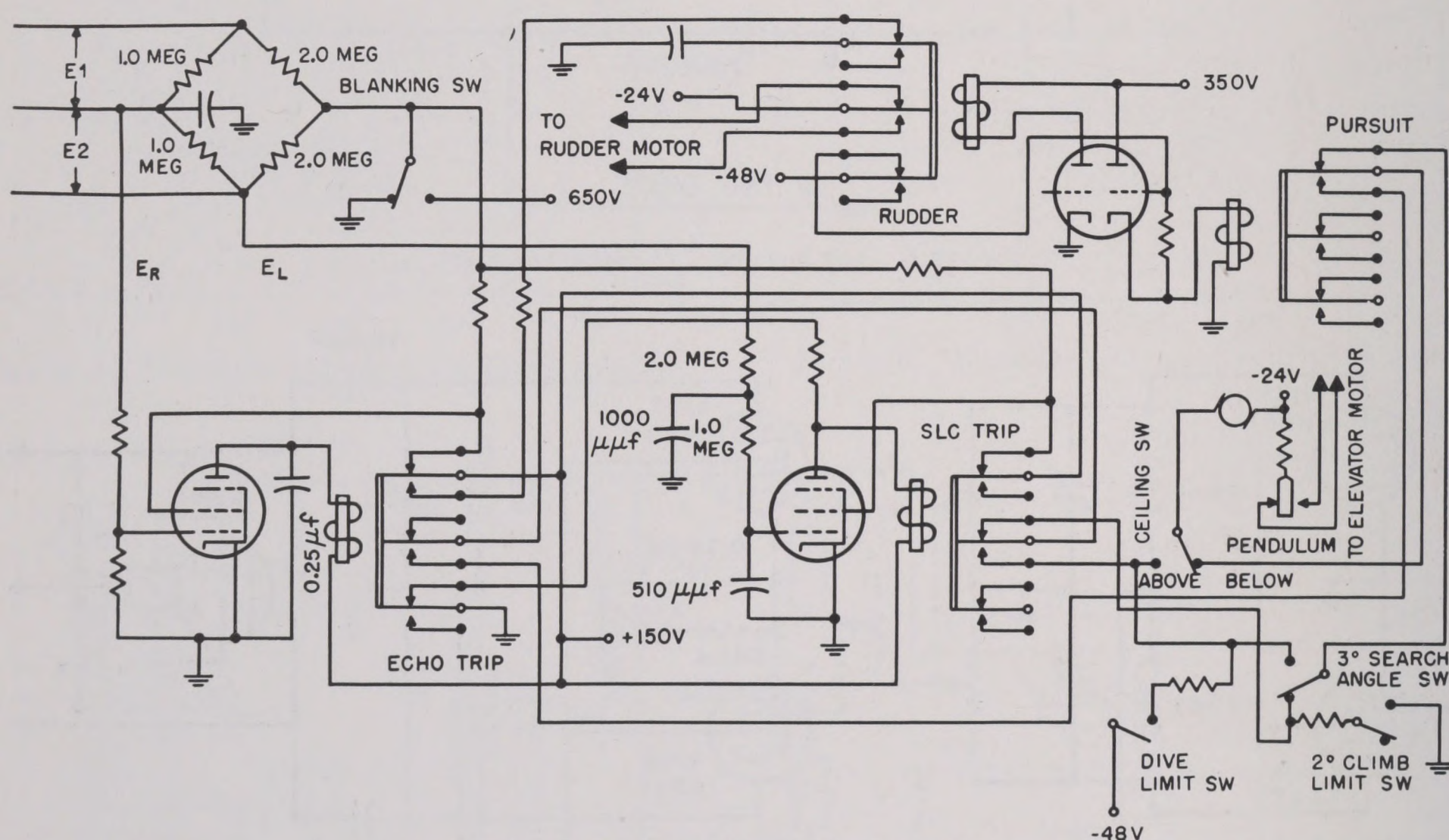


FIGURE 10. Comparison bridge and relays.

transmitter is keyed by means of a switch, operated by the time base, which keys the plate and screen supply of the power amplifiers. A sample of the 60-kc signal generated on the screens of the power amplifier is rectified by means of the TVG diode and stored on a condenser to serve as the gain control bias during the listening interval.

## 18.5

## RECEIVER

When an acoustic signal is received by the transducer the voltages developed on the two halves are impressed on the grids G1 and G2 of V104, Figures 7 and 8. If the acoustic signal arrives on the transducer face from a point dead ahead, the voltages developed in the windings of the two halves of the transducer will be in phase and therefore the voltages

channel amplifier for the receiver. The double potentiometer is used to balance the inputs to the two channels and adjust the relative values of TVG voltage on the grids of V105 and V106. Figure 8 shows the details of the circuit from the grids G1 and G2 to the input of the two-channel amplifier.

After transmission of a pulse by the system, a continuous signal will be received by the transducer because of reverberation in the water. The level of this signal decays quite rapidly with time. The time required for an echo to be received after transmission is directly proportional to the range of the target; therefore, the level of the echo can be expected to decrease as the time interval between transmission and reception increases. A TVG system is used in order to control the sensitivity of the receiver so that it



will not respond to the reverberation but will increase in sensitivity with time following transmission, so that weak signals from long ranges can be used for control. This variable gain is obtained by means of a variable bias applied to the grids of V105 and V106. The bias is obtained by rectifying a portion of the signal appearing on the screen of one of the transmitter power-amplifier tubes by means of the TVG diode, Figure 7, and charging the TVG condenser, Figure 8, with the output of this diode. Immediately after transmission stops, the condenser starts to discharge through the 0.24-megohm resistor to ground thus producing the time variation in bias. No AVC is used in this device.

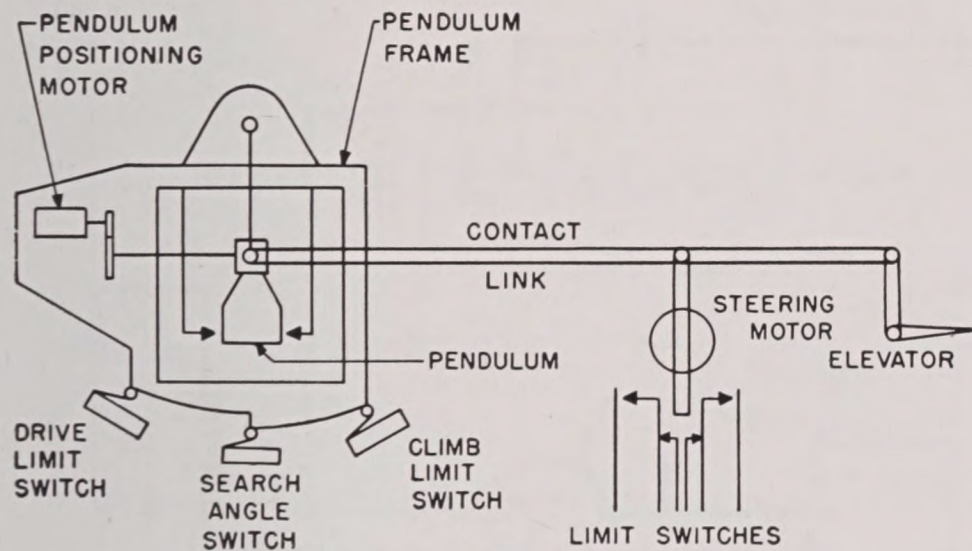


FIGURE 11. Pendulum assembly.

The two-channel amplifier consists of two stages of tuned amplifier for each channel with a system of balancing potentiometers between the two stages to be used to equalize the gain in the two channels. The output of each channel goes to a diode rectifier. These rectifiers are so connected to a bridge that an echo pulse is obtained at one point on the bridge network whenever an echo is received by the transducer. The difference in polarity between two other points on the bridge indicates whether the echo came from above or below the axis of the transducer. The two-channel amplifier is shown in Figure 9 and the comparison bridge is shown in Figure 10.

### 18.6 COMPARISON BRIDGE

There are two conditions to be considered in the comparison bridge shown in Figure 10. Condition 1, when the target is in the same horizontal plane as the axis of the torpedo. In this case, the voltages  $E_1$  and  $E_2$  will be equal and

$$E_R = E_1 = E_2,$$

and

$$E_L = \frac{E_1 - E_2}{2} = 0.$$

Condition 2, when the target is not in the same horizontal plane as the axis of the torpedo. In this case,

$$E_R = \frac{E_1 + E_2}{2},$$

and

$$E_L = \frac{E_2 - E_1}{2}.$$

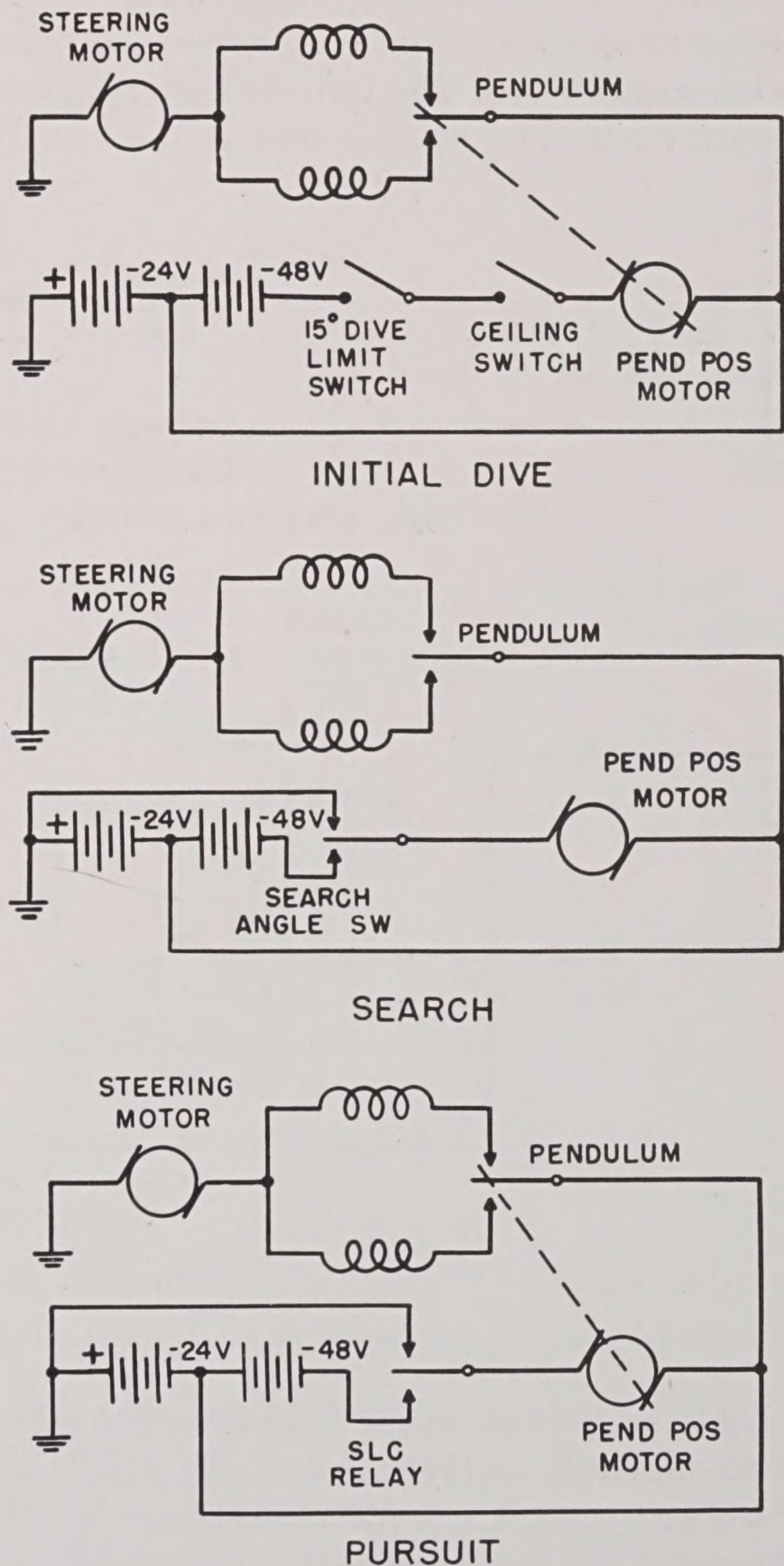


FIGURE 12. Schematic of depth-steering conditions.

Since the input voltages  $A$  and  $B$  of Figure 2 are not the same for condition 2, the values of  $E_1$  and  $E_2$  will be different.  $E_R$  will always be negative regardless of the orientation of the target relative to the axis of the torpedo.  $E_L$  will be positive when the target is on one side of the torpedo axis and negative when it is on the other side.



## 18.7 CONTROL SYSTEM

This control system utilizes two independent steering systems, one for azimuth control and the other for depth control. In the search condition the azimuth control system maintains the rudders in the port position so that the torpedo searches in a port circle. When an echo is received, the voltage  $E_R$  developed in the comparison bridge causes the echo trip-relay to open, which in turn causes the rudders to swing to starboard. The torpedo then goes into a starboard circle. The holding time of this circuit is

condition, and third, the pursuit condition. The elevators are controlled during all three of these conditions by means of a set of contacts operated by a pendulum. The frame in which the pendulum contacts are mounted can be rotated by means of a small motor and the various steering conditions are controlled by the positioning of this frame. Figure 11 shows the relationship of the pendulum frame, the pendulum, the steering motor, and the elevators, whereas Figure 12 shows the electric circuit setups for the three steering conditions. During the initial dive the steering is controlled by the ceiling switch

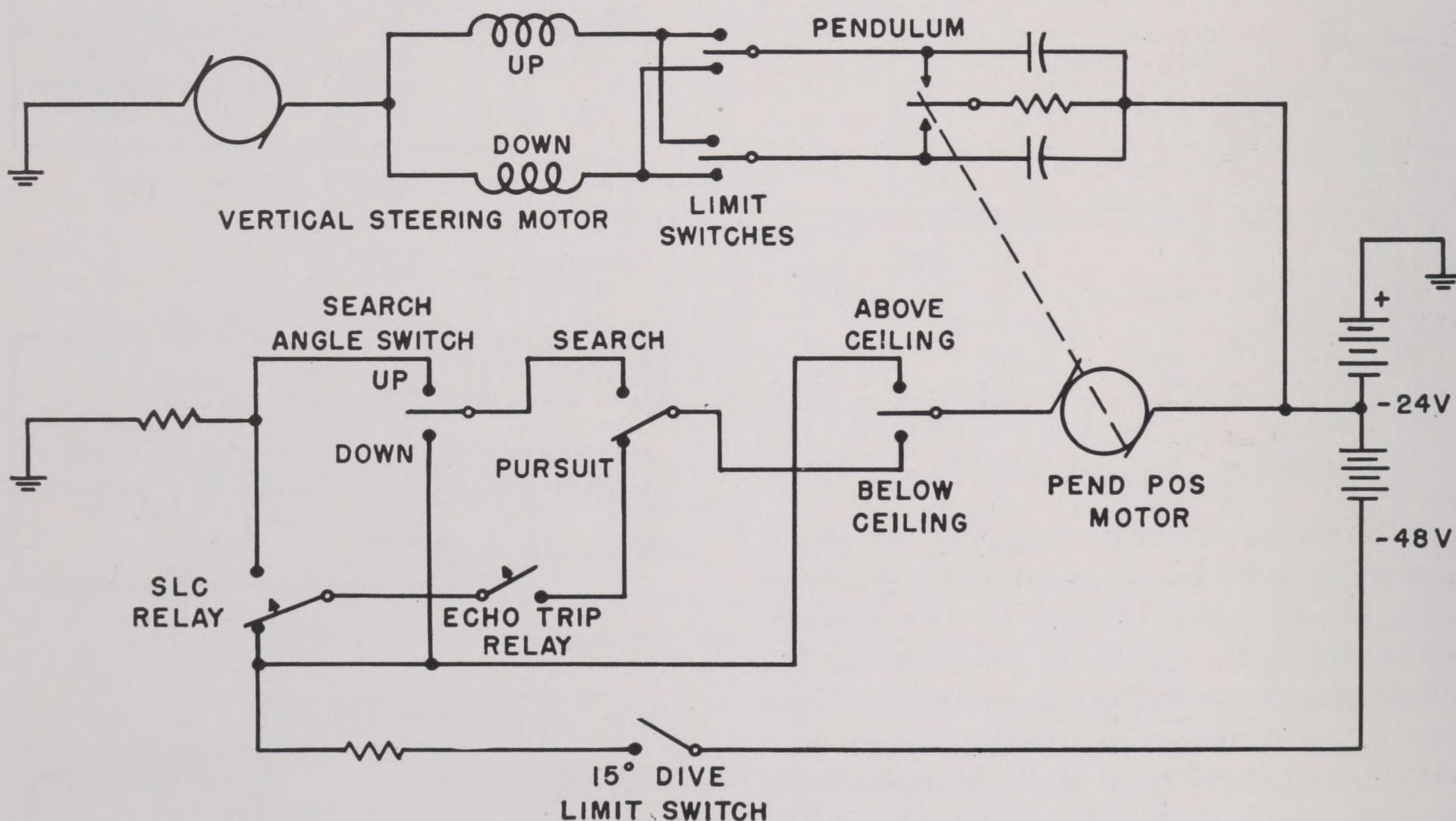


FIGURE 13. Schematic of depth control.

such that the rudders will be held from one echo to the next and will continue to hold for about 1 sec after the last echo of a sequence has been received. At the end of this holding time the rudders will again drop back to the port position. This constitutes an on-off steering system for the azimuth control, and the torpedo will continue to steer on and off the beam of the transducer in the azimuth plane during the entire course of an attack.

The vertical steering system is considerably more complicated. In dealing with this system there are three steering conditions to be considered. First, the condition during the initial dive, second, the search

which operates at a depth of 50 ft, and by the dive angle limit switch which limits the dive angle to 15 degrees. The ceiling switch opens at 50-ft depth and throws the control over to the search angle switch which causes the torpedo to dive at a fixed angle of 3 degrees until a depth of 225 ft is attained, when the search angle is changed to 2 degrees. If an echo is received from a target the pursuit relay is opened and the pursuit condition is set up. Under this condition the positioning of the pendulum frame is controlled by the SLC relay. A schematic of all of these controls is shown in Figure 13. Figure 14 shows schematically the functioning of the various relays in an attack.

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### 18.8 BLANKING CIRCUITS

The following blanking circuits are used to protect the device against steering on false information.

1. The 125-ft blank. This prevents echoes from less than 125 ft range from controlling the torpedo.

duction is permanent unless the torpedo misses the target, in which case the range returns to normal.

3. The 6- and 9-degree blanks. These are range-reduction circuits designed to avoid bottom reflections. When the pitch of the torpedo reaches 6 degrees down, the range is reduced to 1,500 ft. Also

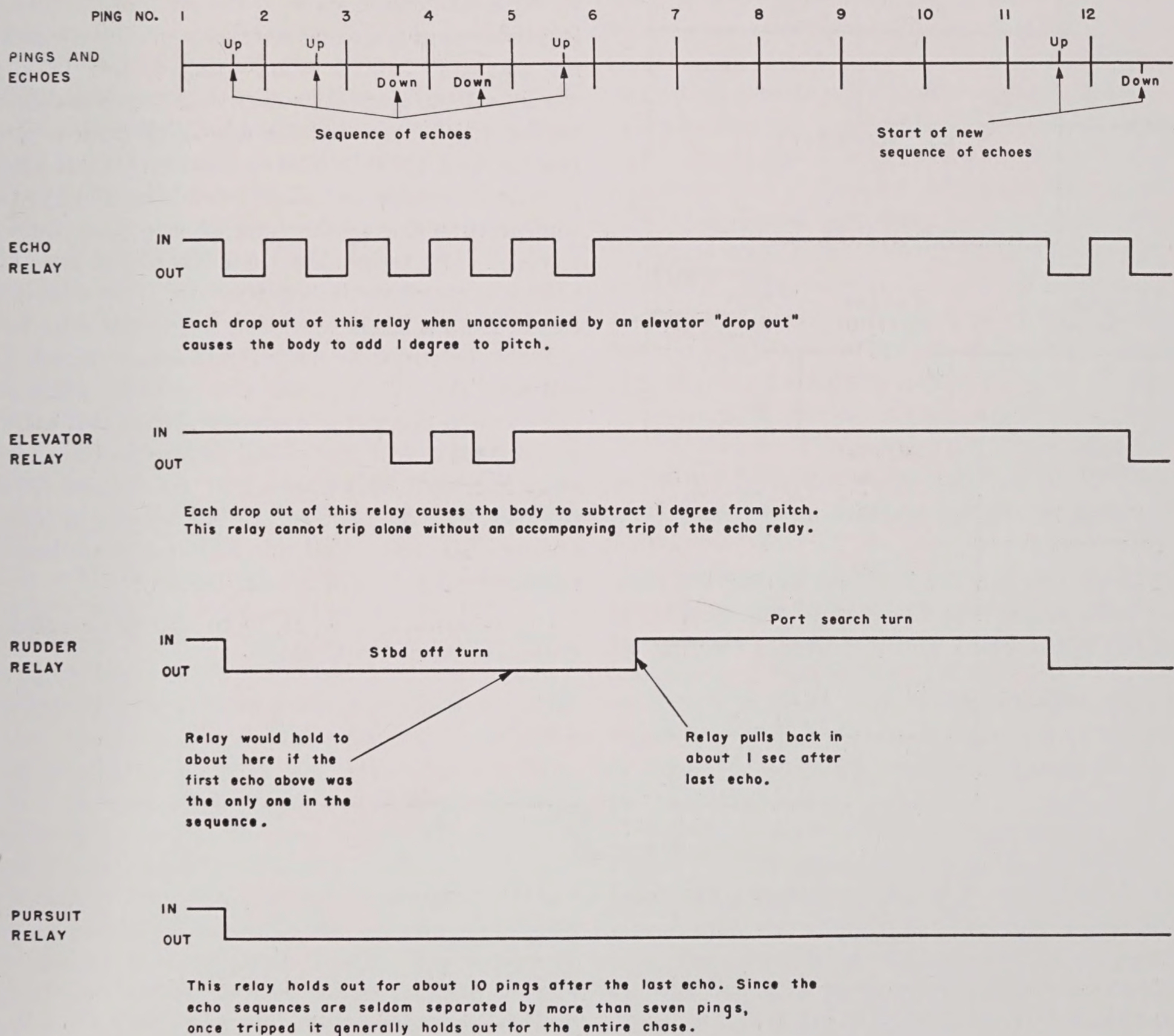


FIGURE 14. Schematic of operation sequences.

Without this provision the torpedo will go around the bow of the target.

2. The 500-ft blank. This is a range-closing circuit. Once an echo has been received from a range less than 500 ft the range is reduced to 500 ft. This range reduction is used to prevent steering on echoes which are the result of reflection from the target to the bottom then back to the torpedo. This range re-

duction is permanent unless the torpedo misses the target, in which case the range returns to normal. These circuits are all operated by means of cams and microswitches operated from the main motor shaft. The torpedo pitch is measured by mercury switches.

Figure 15 is a schematic of the complete blanking system. The switches C1, C2, C3, and C4 are operated by the cams driven by the main motor. Blank-



ing is achieved by applying  $-26$  v directly to the screens of the first stages of the two-channel ampli-

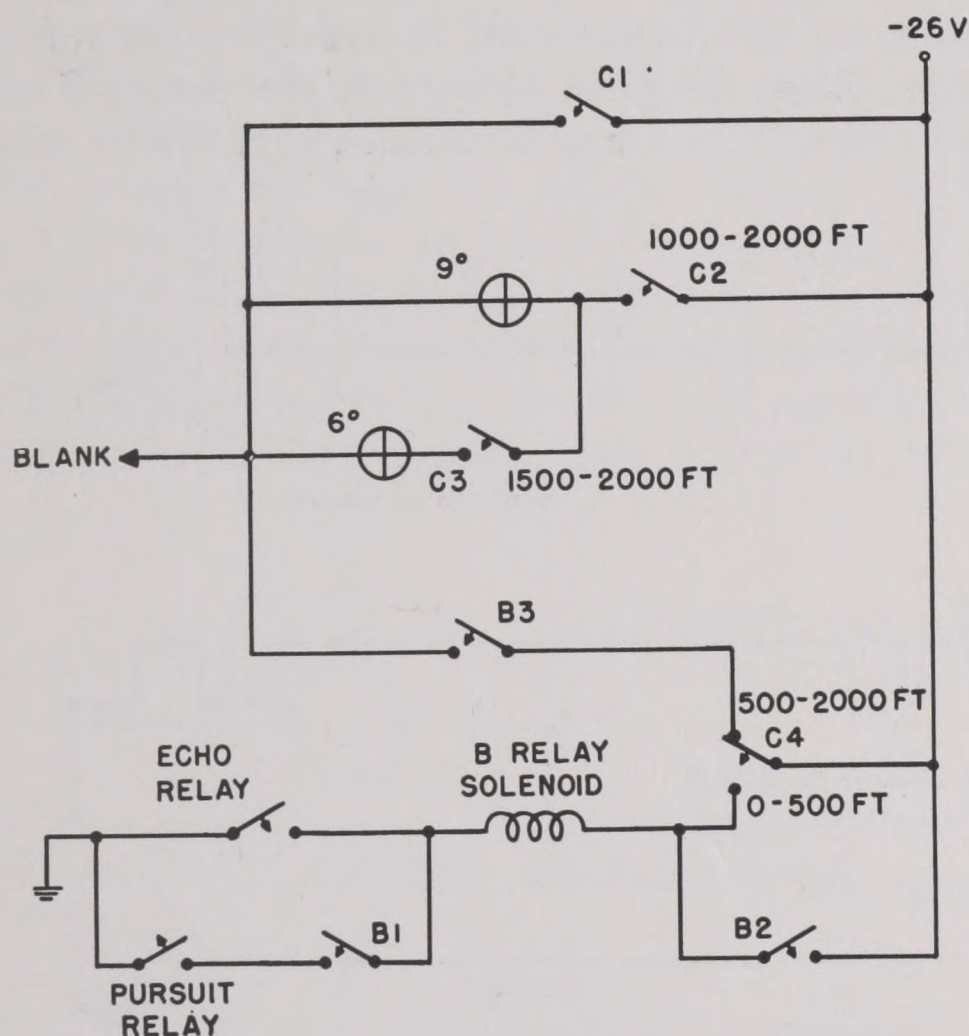


FIGURE 15. Schematic of blanking circuits.

fier. The cam switch  $C1$  is closed during the time echoes from ranges 0 to 125 ft can come in. This is called the 125-ft blank and it prevents steering on

echoes from ranges less than 125 ft. The two mercury switches marked 9 degrees and 6 degrees are closed for angles greater than 9 degrees and 6 degrees of pitch respectively. The cam  $C2$  is closed after the time necessary for receipt of echoes from ranges greater than 1,000 ft and  $C3$  is closed after the time necessary for receipt of echoes from 1,500 ft. With this arrangement, if the pitch of the torpedo is greater than 6 degrees the receiver will be blanked for any echo from a range greater than 1,500 ft, whereas if the pitch is greater than 9 degrees the receiver will be blanked for any echo from a range greater than 1,000 ft. The cam switch  $C4$  is a single-pole double-throw switch which is closed in the bottom position during the time when echoes could be received from ranges less than 500 ft and after this time it is closed in the top position. If an echo is received from a range less than 500 ft the echo relay will also be closed so relay  $B$  will be energized. The contacts  $B1$ ,  $B2$ , and  $B3$  are contacts which are closed when relay  $B$  is energized. When this relay is once closed it will stay closed as long as the pursuit relay is closed. This means that via  $C4$  and  $B3$  the receiver will be blanked for all echoes of ranges greater than 500 ft and this blanking condition will remain until the pursuit relay opens.<sup>a</sup>

<sup>a</sup> See references 6, 9, 10, 14, 20, 26 and 28 for additional material on topics in this chapter.



## Chapter 19

# HARVARD UNDERWATER SOUND LABORATORY NO181 SYSTEM

19.1

### INTRODUCTION

THE HARVARD Underwater Sound Laboratory [HUSL] undertook the development of an echo-ranging torpedo in the summer of 1942, utilizing a doppler-controlled enabling system as a protection against steering on surface, bottom, or wake echoes. A special transducer was developed to operate at 60 kc which could be utilized both as a projector and a hydrophone. The torpedo was designed as an antisubmarine weapon and the electronic gear was so designed that it could replace the standard electronic gear in the project 61 mine. After preliminary field tests on two experimental units, six electronic panels were built to convert the project 61 mine to echo ranging with all components engineered so that the system could be put in production with a minimum of redesign. This design was designated as NO181F.

The units were tested against an echo repeater used to simulate a submarine in August 1944. The performance in these tests was quite satisfactory. The units successfully attacked an echo repeater after bench tests indicated that the electronic gear was in satisfactory operating condition. Some difficulty was encountered in the tests against a submarine, because of the difference between an echo repeater and a submarine as a target. The revisions necessary in the electronic gear in order to overcome these difficulties would not have been serious. However, since the General Electric version of NO181 had already been selected for this application it seemed desirable to do some major revision to simplify the system and to increase the transmitter power output. This program resulted in the development of the Ordnance Research Laboratory [ORL] project 4 version which will be described in Chapter 21.

The system uses a single transducer made up of 32 small laminated magnetostriction elements mounted on a rubber diaphragm about 6 in. in diameter. The 32 elements are divided into four quadrants and the elements in each quadrant are connected in series. The terminals for each quadrant are then brought out separately in a cable. Three transformers

are provided for coupling the transducer to the electronic gear, one to match the plate circuits of the transmitter power amplifier to the transducer and two which match the transducer to the grids of the tubes in the first stage of the receiver. By means of these transformers, a series-tuned circuit and eight resistors, the following features are achieved: (1) Transmission and reception are performed with the same transducer elements without any form of switching being necessary; (2) the plate circuit of the transmitter power amplifier is properly matched to the transducer; (3) 20 db of voltage gain is provided between the transducer and the input of the receiver, and, (4) five signals are provided at the input of the receiver. The voltage difference between one pair is produced by a phase difference between the signals on the two port quadrants and the two starboard quadrants of the transducer. Similarly, the voltage difference between another pair is produced by a phase difference between the signals on the two top quadrants and the two bottom quadrants of the transducer. It is possible therefore to steer in both azimuth and depth with the information thus provided. The fifth signal is a measure of the total acoustic signal on the transducer and is used to operate the enabling system.

A block diagram of the electronic gear is shown in Figure 1. The operating frequency is 60 kc. The transmitter power output is 80 watts of electrical power with the transducer efficiency about 35 per cent. The transmitted pulses are at 0.65-sec intervals and the length of the transmitted pulses is 30 msec. Since this is an antisubmarine device, acoustic steering control is in both azimuth and depth. No *time-varied gain* [TVG] is used but an *automatic volume control* [AVC] is used to allow the receiver sensitivity to be controlled by the level of the reverberation. The enabling of the system is done by a combination of an amplitude gate and a doppler gate. The amplitude gate requires that an echo have a level at least 5 db above reverberation level and that it persist for at least 5 msec. The doppler enabling system sets a requirement of 60 c frequency difference between the reverberation and an echo. The



system was designed to convert the project 61 listening torpedo to an echo-ranging torpedo. The body used is the standard project 61 body with very little modification besides the substitution of the echo-ranging electronic gear for the listening electronic gear formerly used.

in the horizontal plane. Figure 3 is the pattern obtained when 0.55 watt of power is transmitted continuously. Figure 4 is the pattern obtained when an electric power of 1.38 kw is transmitted in 1-msec pulses. It will be noted that the pattern at high power levels is somewhat sharper than at low power

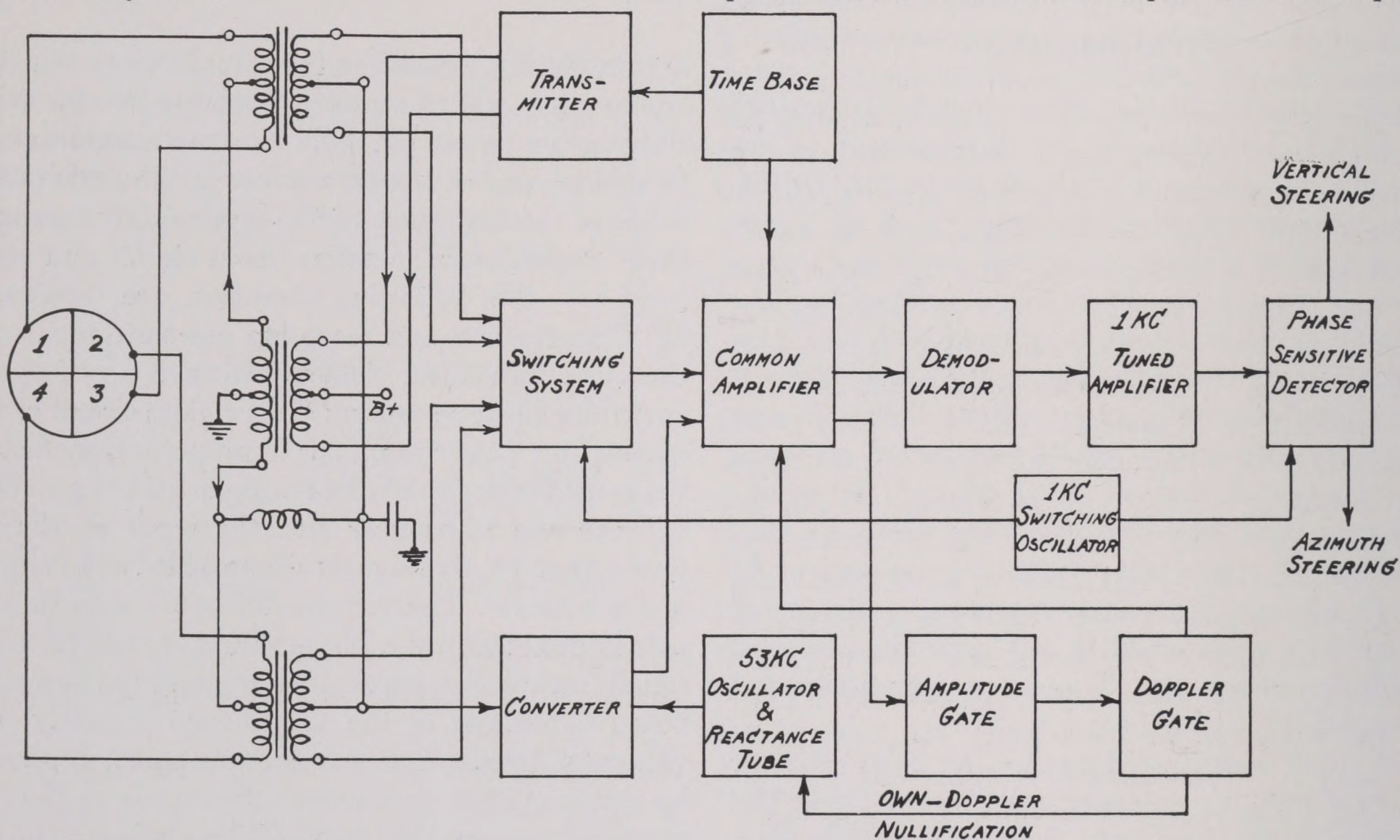


FIGURE 1. Block diagram of Harvard NO181 F.

## 19.2

### TRANSDUCER

The transducer used was made up of an array of laminated-stack magnetostrictive elements. These elements were identical with those used in the General Electric device described in Chapter 18 and illustrated in Figure 2 of Chapter 18. The version of this transducer used in the HUSL system differs in the arrangement of the units in the transducer and the diameter of the diaphragm, since in this case a symmetrical system in the vertical and azimuth planes is desired. Figure 2 shows the arrangement of the elements in this transducer and the numbers indicated on the elements are proportional to the number of turns in the windings on the elements. This shading of the windings on the elements is for the purpose of producing the desired patterns. The frequency response of this transducer is similar to that of the one used in the General Electric version and is indicated in Figure 4 of Chapter 18. Figures 3 and 4 of Chapter 19 show the pattern of the transducer

levels because the four central elements are approaching saturation. The curves of Figures 3 and 4 show the dynamic sound pressure at 1 m as a function of the angle. The following are the numerical characteristics of a representative transducer. The pattern is 9 db down, 10 degrees off the axis. The overall directivity index is -23 db and the first minor lobes are at least 25 db down. The impedance of each quadrant is  $25 + j80$ , and since the transducer is connected with the quadrants in series-parallel, this is the impedance of the entire transducer in actual use. During transmission, 74 db above 1 dyne per sq cm is developed at a range of 1 m per volt of electric signal applied to the transducer. The receiving sensitivity is -86 db below 1 volt per dyne per sq cm. The efficiency reaches a maximum value of 38.5 per cent at an electric power input of 800 watts. At a power input of 1.38 kw the acoustic power output is 403 watts with an efficiency of 29.2 per cent. Since the transducer is symmetrical, its pattern in the vertical plane is identical to the pattern in the horizontal plane.

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## 19.3

## INPUT CIRCUIT

The input circuit used has the advantage that it combines the step-up transformation from the transducer impedance to the grid impedance with a lag-line action all in one step. Furthermore, it permits transmission without need for disconnecting the receiving system. The circuit for this input system is shown in Figure 5. In this circuit, quadrants 1 and 3 of the transducer are connected in parallel as are also quadrants 2 and 4, but, as indicated in the diagram, quadrants 2 and 4 are connected so as to give voltages 180 degrees out of phase with quadrants 1 and 3 when the sound is normally incident on the

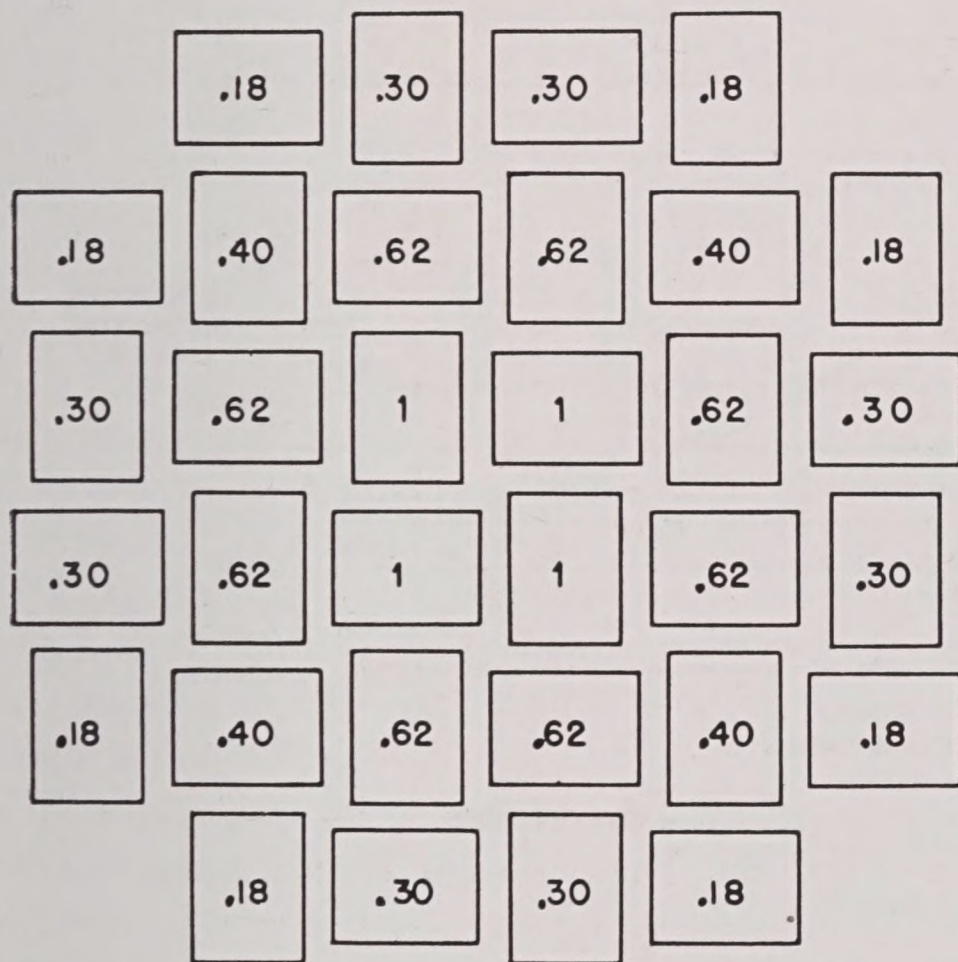


FIGURE 2. Array of elements in the transducer.

transducer. The voltages developed across the two input transformers thus vanish for sounds normally incident and are proportional to the difference between the voltages on the corresponding pairs of quadrants when the sound is not normally incident. It is very important that the coupling between the two halves of the input transformer be as tight as possible. This is particularly important for transmission since the transmitting signal is fed through the center taps of the input transformer and if the coupling is not tight, there will be a large voltage drop across the two halves; hence the voltage appearing at the center tap will not be the voltage appearing across the transducer itself.

The operation of the circuit shown in Figure 5 may be best described by computing the voltages

appearing at various points in the circuit, assuming that the voltages developed by each of the four quadrants of the transducer, and the impedances, are as indicated in Figure 5. It is to be noted that

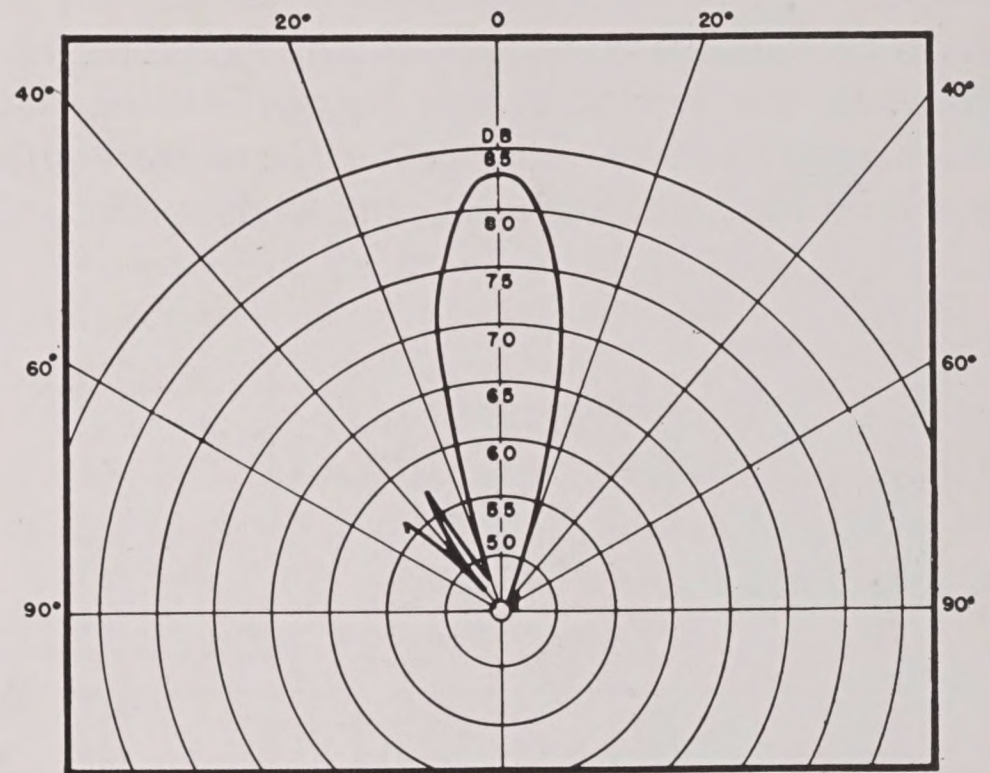


FIGURE 3. Transmitting pattern for 0.55 watt.

the condensers  $Y_i$  series tune each quadrant of the transducer and similarly the condenser  $Y_s$  series tunes the inductive reactance of the coil  $X_s$ . The circuit  $X_s Y_s$  will be referred to as the 90-degree cir-

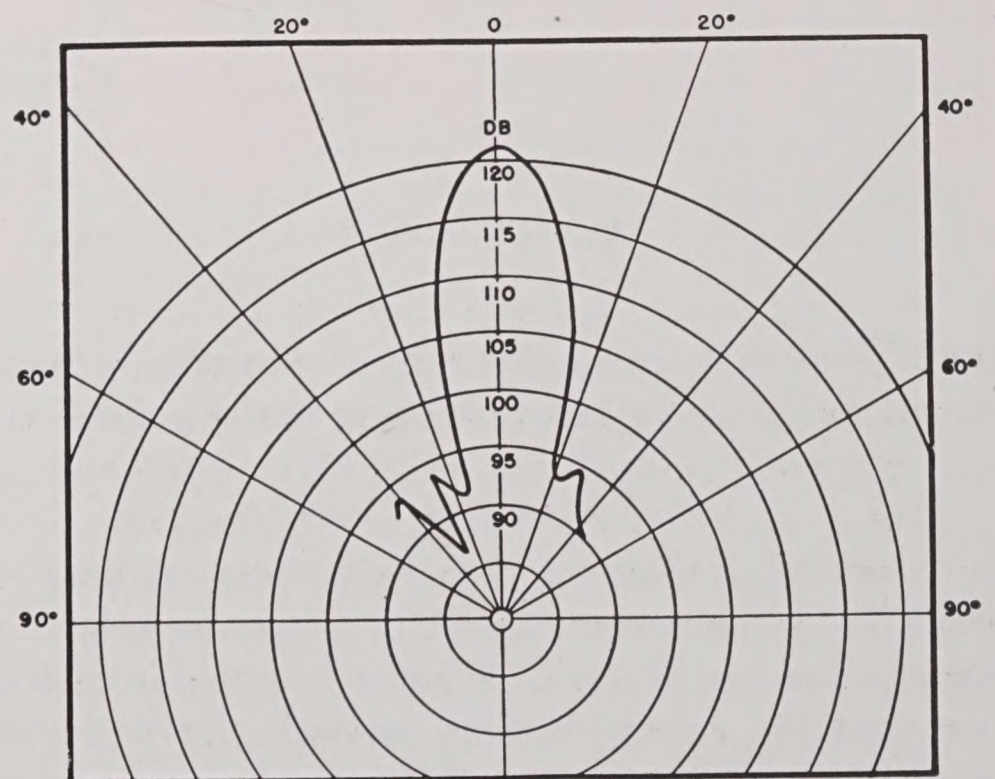


FIGURE 4. Transmitting pattern for 1.38 kw.

cuit since it is tuned so that there is a 90-degree phase shift between the two ends of  $X_s$ .

The resistance  $R_L$  is assumed to match the internal resistance of quadrants 1 and 3 or 2 and 4 in series so that

$$R_L = 2N^2 R_1. \quad (1)$$

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If this is the case, the voltages developed across  $R_L$  are

$$\frac{1}{2}N(e_1 - e_3), \quad (2)$$

and

$$-\frac{1}{2}N(e_2 - e_4),$$

on the left and right hand sides of the diagram respectively. In the circuit as used,  $R_L$  was omitted and the value of  $R_B$  was so selected that the network provided the load  $R_L$ . Neglecting the loading effect of

$$A: \frac{1}{2}N \frac{R_L}{R_L + 2N^2R_1} (e_1 - e_3) - \frac{\frac{1}{4}jY_s}{R_s + \frac{1}{4}R_1} (e_1 + e_2 + e_3 + e_4) \quad (5a)$$

$$B: \frac{1}{2}N \frac{R_L}{R_L + 2N^2R_1} (e_3 - e_1) - \frac{\frac{1}{4}jY_s}{R_s + \frac{1}{4}R_1} (e_1 + e_2 + e_3 + e_4) \quad (5b)$$

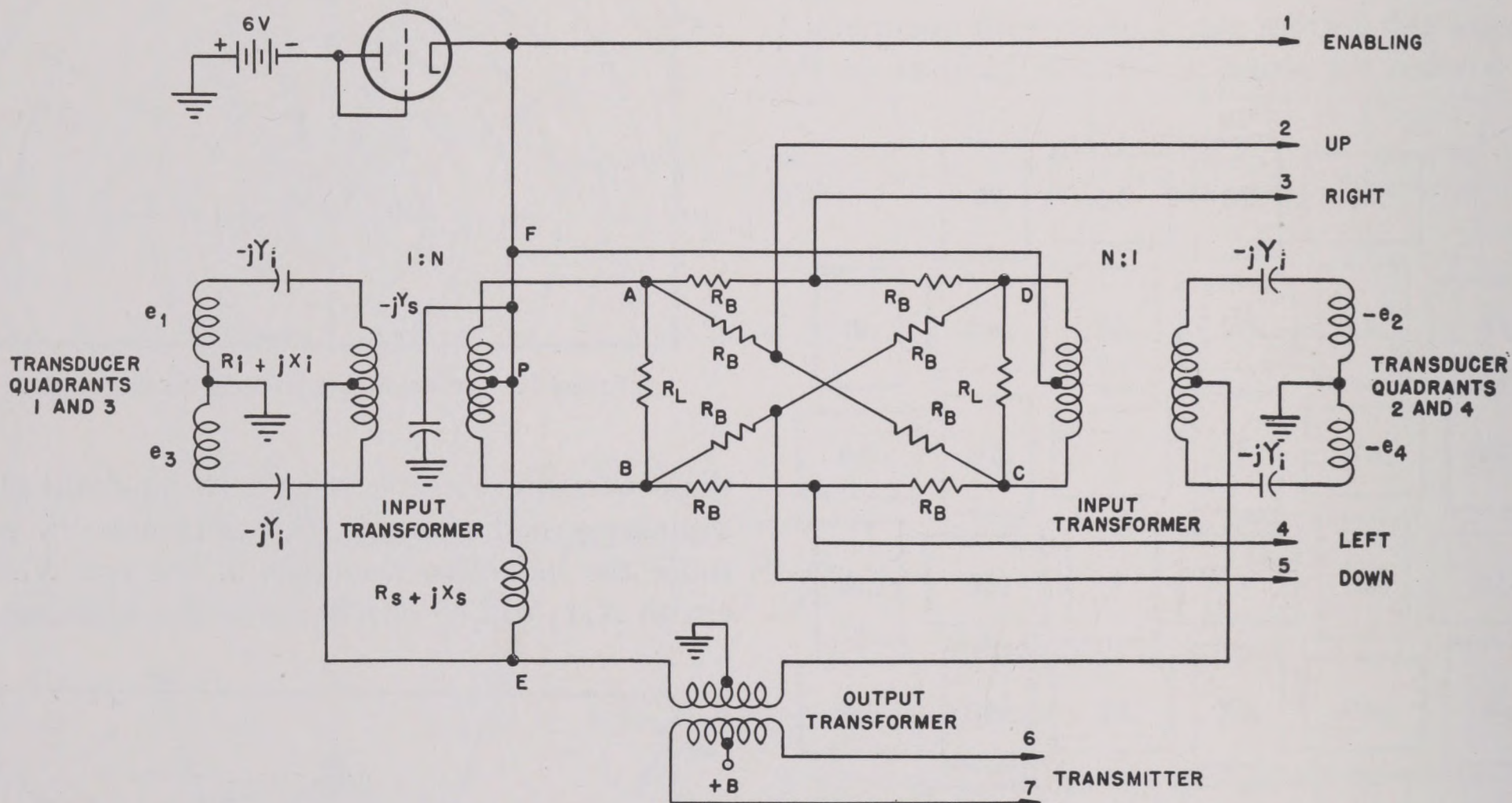


FIGURE 5. Input circuit.

the 90-degree section consisting of the series-tuned circuit  $X_s Y_s$ , the voltage appearing at the point  $E$  is:

$$\frac{1}{4}(e_1 + e_2 + e_3 + e_4). \quad (3)$$

It is essential that the two halves of the output transformer be very tightly coupled in order to achieve the result (3). The factor  $\frac{1}{4}$  arises from the fact that the voltage is that appearing across only one-half the secondary of the output transformer. The impedance looking back from point  $E$  looks like all four quadrants in parallel, namely  $\frac{1}{4}R_i$ . The voltage developed at point  $F$  after the step-up circuit is therefore given by:

$$\frac{-jY_s}{R_s + \frac{1}{4}R_i} \frac{1}{4}(e_1 + e_2 + e_3 + e_4). \quad (4)$$

The voltages appearing at points  $A$ ,  $B$ ,  $C$ , and  $D$  are, respectively:

$$C: \frac{1}{2}N \frac{R_L}{R_L + 2N^2R_1} (e_4 - e_2) - \frac{\frac{1}{4}jY_s}{R_s + \frac{1}{4}R_1} (e_1 + e_2 + e_3 + e_4) \quad (5c)$$

$$D: \frac{1}{2}N \frac{R_L}{R_L + 2N^2R_1} (e_2 - e_4) - \frac{\frac{1}{4}jY_s}{R_s + \frac{1}{4}R_1} (e_1 + e_2 + e_3 + e_4) \quad (5d)$$

For simplicity of notation, let

$$\frac{NR_L}{R_L + 2N^2R_1} = Q_D, \quad (6)$$

$$\frac{Y_s}{R_s + \frac{1}{4}R_1} = Q_s.$$

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In terms of this notation the voltages appearing at the four steering grids are as follows:

$$\text{RT: } -\frac{1}{4}KQ_s(e_1 + e_2 + e_3 + e_4) + \frac{1}{4}Q_D(e_1 + e_4 - e_2 - e_3), \quad (7a)$$

$$\text{LFT: } -\frac{1}{4}jQ_s(e_1 + e_2 + e_3 + e_4) - \frac{1}{4}Q_D(e_1 + e_4 - e_2 - e_3), \quad (7b)$$

$$\text{UP: } -\frac{1}{4}jQ_s(e_1 + e_2 + e_3 + e_4) + \frac{1}{4}Q_D(e_1 + e_2 - e_3 - e_4), \quad (7c)$$

$$\text{DN: } -\frac{1}{4}jQ_s(e_1 + e_2 + e_3 + e_4) - \frac{1}{4}Q_D(e_1 + e_2 - e_3 - e_4). \quad (7d)$$

The right and left voltages may be written in the form:

$$\text{RT: } -jV_0(e_1 + e_4)e + j\alpha + (e_2 + e_3)e - j\alpha, \quad (8a)$$

$$\text{LFT: } -jV_0(e_1 + e_4)e - j\alpha + (e_2 + e_3)e + j\alpha, \quad (8b)$$

when  $V_0 = \frac{1}{4}Q_s^2 + Q_D^2$ ,

and

$$\tan \alpha = \frac{Q_D}{Q_s}.$$

It is thus seen that the final output voltages are similar in angular dependance to what would be obtained with a lag line of angle  $2\alpha$  between the right and left halves of the transducer. Similarly the effect of a lag line between the bottom and top halves is obtained at the UP and DN outputs. Referring back to equation (6) we see that the equivalent lag-line angle is given by:

$$2\alpha = 2 \tan^{-1} \frac{Q_D}{Q_s} = 2 \tan^{-1} \frac{NR_L}{R_L + 2N^2R_1} \frac{R_s + \frac{1}{4}R_1}{Y_s}.$$

As an example, in the Harvard NO181F system,  $Q_s$  is 10,  $N$  is 15.2, and  $R_L = 2N^2R_i$ , whence  $Q_D = 7.6$ . Hence, the equivalent lag-line angle is 74 degrees.

The transmitting behavior of the circuits is regulated by the biased diode connected from the secondary center taps of the input transformers to ground. When the voltage at this point exceeds the bias on the diode, the latter shunts the condenser  $Y_s$  and spoils the  $Q$  of the tuned circuit  $X_sY_s$  so that this circuit, which has been termed the 90-degree circuit, does not load the transmitter appreciably. This feature requires for its proper operation that the diode have a low-resistance d-c return to ground, which in the present case is provided by the series coil  $X_s$  and the secondary winding of the output transformer. If the input transformers are properly center-tapped, the voltages developed across the two halves in transmission tend to cancel, with the result that the

inputs provide negligible loading of the transmitter even though the secondaries are terminated. Considerable unbalance in the input system may be tolerated without appreciable loss of power.

The bias on the diode is adjusted so that it is never exceeded by the signal voltage appearing between  $F$  and ground during reception. In that case the voltage appearing at  $F$ , and hence on terminal 1, gives simply the unshifted receiving pattern, which may be used as desired. In this system it provides the signal input for the channel which controls the AVC and actuates the doppler gate system.

Figure 6 shows the voltage differential between terminals 3 and 4 or 2 and 5 of Figure 5 as a function of electrical phase difference between signals on the two halves of the transducer determined experimentally with a representative unit.

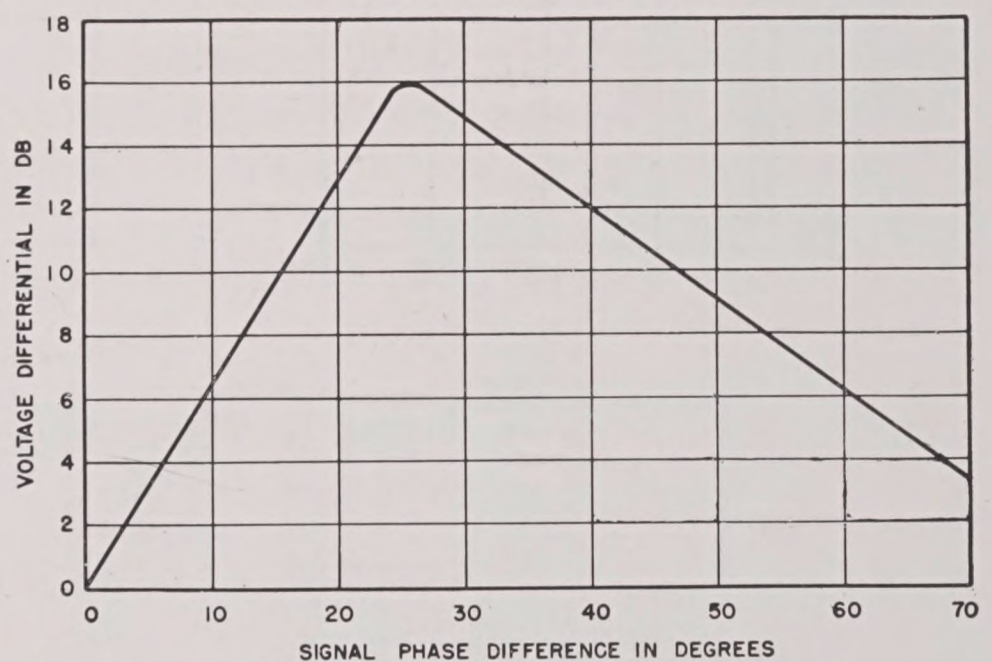


FIGURE 6. Voltage differential as a function of signal phase difference between signals from the two halves of the transducer.

Figure 7 shows a set of curves obtained from one of the experimental units. These indicate the performance of the transducer and input circuit in both transmission and reception. The curves indicating performance in reception were obtained by mounting a source so that it made various angles with the axis of the transducer and determining the relative pulse level as a function of angle which was necessary to actuate the steering relays in the system in one case, and in the other the level necessary to operate the enabling system. The signal which operates the enabling system is taken from terminal 1 in the diagram of Figure 5. The third curve shows the relative level of the transmitted pulse as a function of the angle off the axis of the transducer and it was determined by measuring the levels of signal received by a hydrophone when the transducer was excited by means of the transmitter in the torpedo.



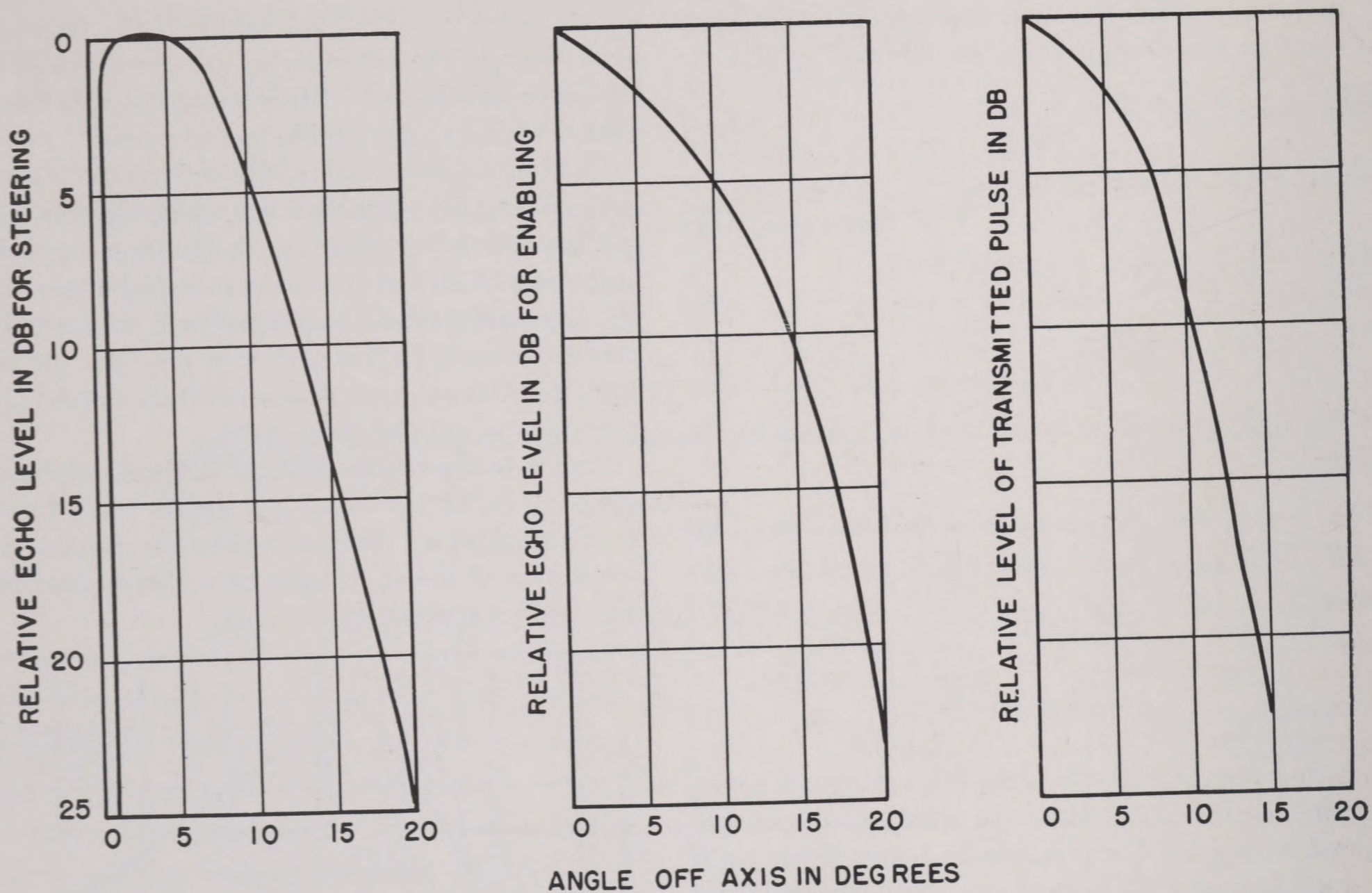


FIGURE 7. Characteristics of transducer and input circuit.

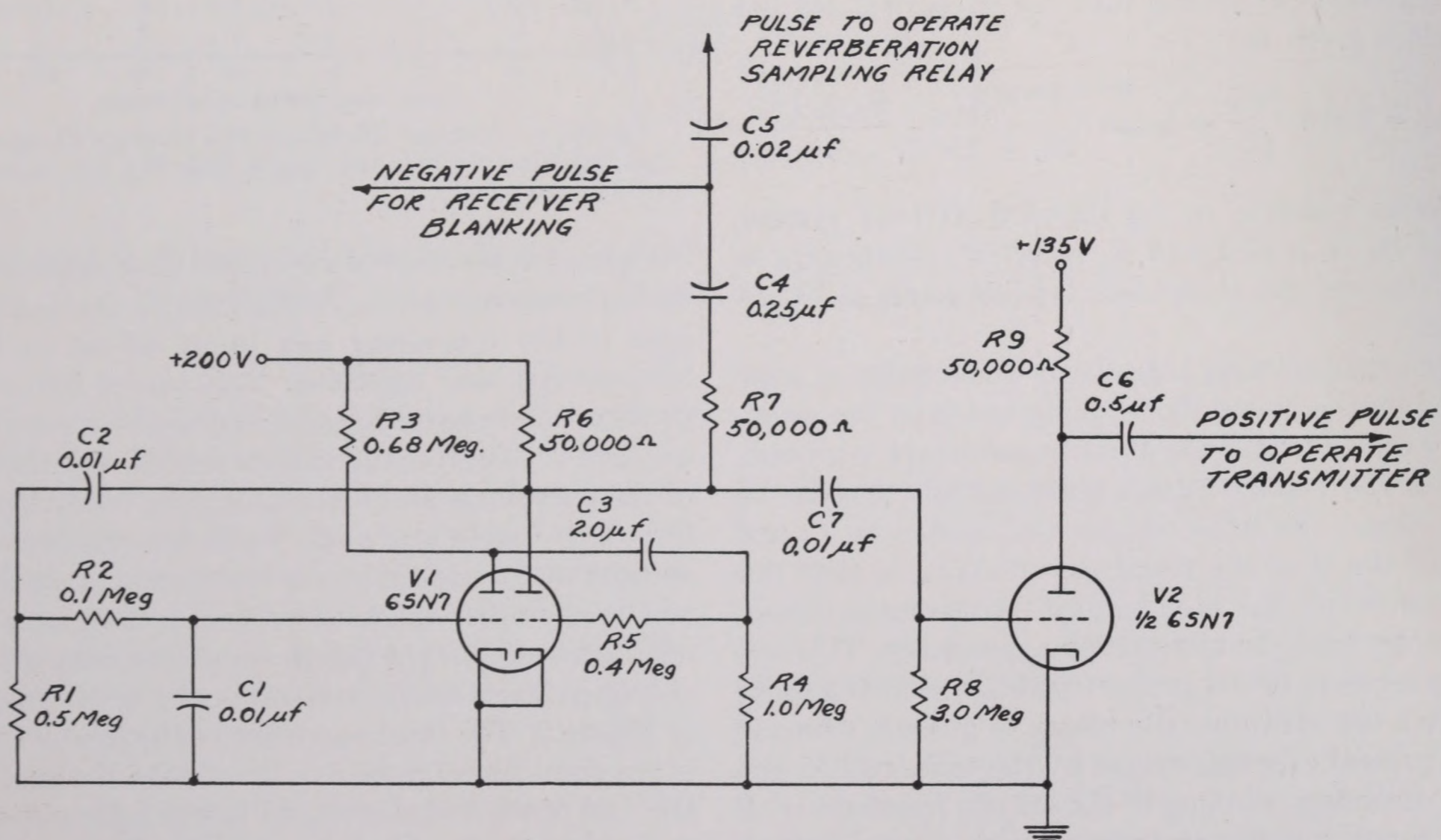


FIGURE 8. Time-base circuit.

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19.4

## TIME BASE

The system is designed to transmit 30-msec pulses at 0.7-sec intervals. In order to accomplish this a multivibrator is used as a time base. The transmitter is designed so that it is actuated by a positive pulse

The multivibrator circuit incorporating the tube V1 in Figure 8 determines both the 0.7-sec interval and the 30-msec pulse length. The resistor R3 and the condenser C3 determine the 0.7-sec interval while the resistor R1 and the condenser C2 determine the length of the pulse. The 30-msec pulse

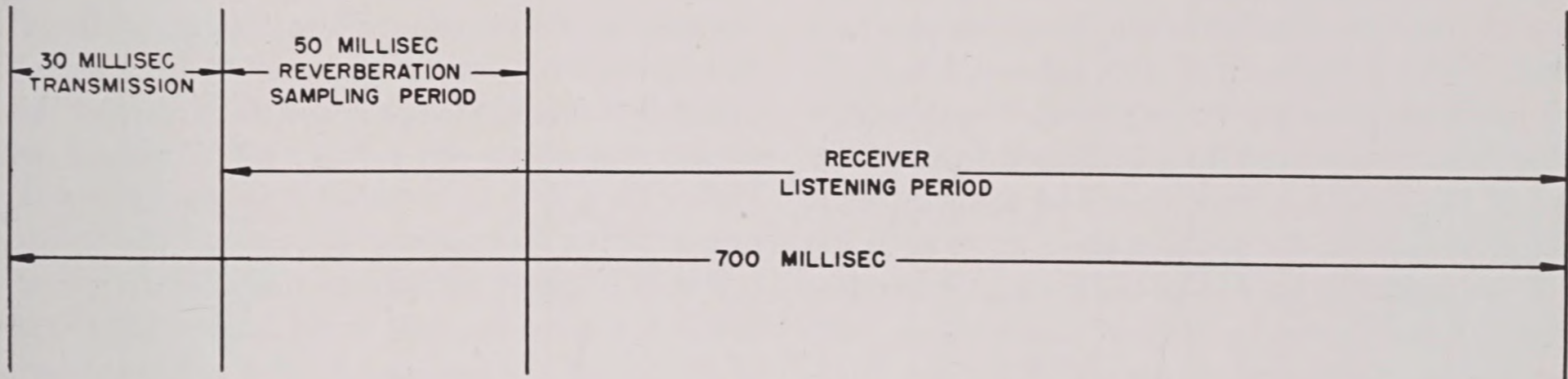


FIGURE 9. Sequences controlled by the time-base circuit.

and it is also necessary to blank the receiver by means of a negative pulse which is generated simultaneously with the transmitter-actuating positive pulse. In addition, it is necessary to operate a relay immediately following the end of the transmitted

which is generated by the system is a negative pulse. The positive pulse used to actuate the transmitter is obtained by means of the phase-inverter stage V2. Figure 9 shows schematically the sequences which are controlled by the time base.

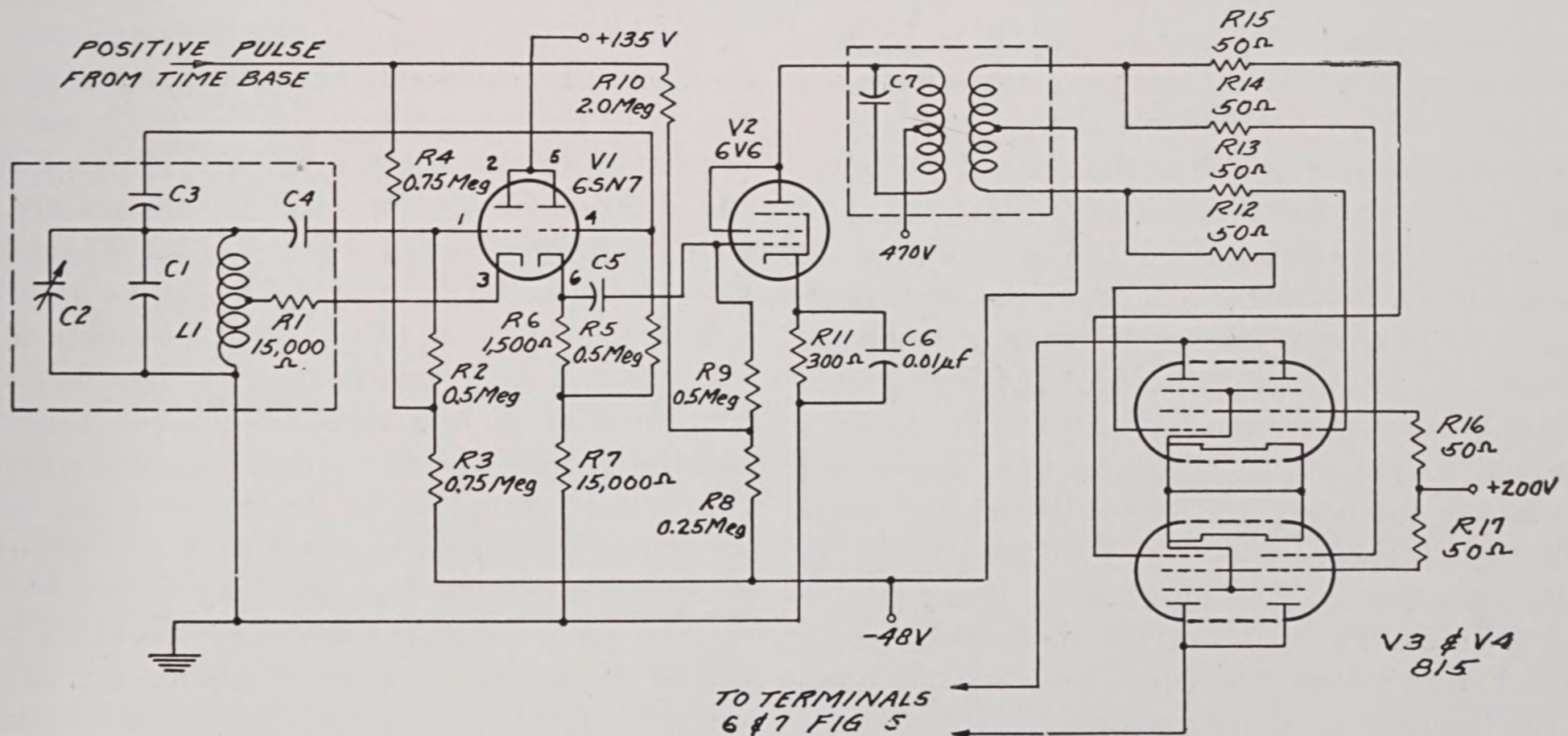


FIGURE 10. Transmitter.

pulse and hold the relay closed for a period of 50 msec. The operation of this relay circuit is accomplished by differentiating the negative pulse by means of the condenser C5 in Figure 8 so that the relay operates on the positive pip at the end of this pulse. A holding time is incorporated in the relay amplifier circuit to enable it to hold the relay closed for the necessary 50-msec interval.

19.5

## TRANSMITTER

Since this device utilizes the doppler frequency shift caused by the motion of the target through the water to enable the steering amplifier, it is necessary that the frequency stability of the transmitter be quite good. In order to accomplish this, care was required in the design of the transmitter oscillator and

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in the means of coupling the oscillator to the power amplifier. The 1-2-3 section of the tube V1 in Figure 10 is the transmitter-oscillator stage. The frequency-determining components are the inductance L1 and the condensers C1 and C2. The oscillator is coupled to a buffer stage by means of the condenser C3. The buffer stage uses the 4-5-6 section of the tube V1. The 6V6 tube V2 is the driver stage which is used to drive the pair of 815 tubes V3 and V4 which constitute the power amplifier. The oscillator and the driver stage are normally biased to cutoff by means of the -48-v connection. The transmitter is actuated by means of a positive pulse applied to the grid of the oscillator by way of the resistor R4 and to the grid of the driver by way of the resistor R10. These stages are then made operative for the duration of the 30-msec positive pulse from the time base circuit. The output of the power-amplifier stage is fed to terminals 6 and 7 in Figure 5. These are the terminals of the primary of the power-output transformer which is an integral part of the input circuit. The supply voltage for the transmitter is applied to the center tap of the primary winding of the power-output transformer. The electric power output of the transmitter is about 80 watts resulting in an acoustic power output from the transducer of about 28 watts. The power supply for the screens and the plates of the power amplifier as well as the plate of the driver stage is a special battery which generates 470 v for the plate supply, and a 200-v tap is taken for the screen supply. In order to reduce the size of this battery, a 40- $\mu$ f electrolytic condenser was connected between the 470-v terminal and ground, and a 80- $\mu$ f electrolytic condenser was connected from the 200-v terminal to ground. This arrangement allows the condensers to supply the very high current drain necessary during the interval of transmission and the battery charges the condensers again during the listening period. The plates of the multivibrator tube V1 in Figure 8 were also driven from the 200-v tap on the transmitter battery. Another battery with a 135-v tap was used for the receiver power supply. This was the source for the + 135 v for the transmitter oscillator and buffer stages.

## 19.6

## STEERING RECEIVER

The steering receiver utilizes the output from terminals 2, 3, 4, and 5 of the input circuit indicated in Figure 5. As was pointed out in Section 19.3, the voltage difference between terminals 3 and 4 is de-

termined by the electrical phase difference between the signals on the right and left halves of the transducer, whereas the voltage difference between the signals appearing on terminals 2 and 5 is determined by the electrical phase difference between the signals on the top and bottom halves of the transducer. If an echo is received from a direction to the right of the axis of the transducer the voltage on terminal 3 will be higher than that at terminal 4, whereas if the signal is received from a point to the left of the axis of the transducer the voltage at terminal 4 will be higher than that at terminal 3. In the same way, signals arriving from above the axis of the transducer produce a higher voltage at terminal 2 than at terminal 5, whereas signals arriving from below the axis of the transducer produce a higher voltage at terminal 5 than at terminal 2. If the signal arrives from a point on the axis of the transducer, the signals developed at all four of these terminals will be the same.

In the steering receiver, shown in Figure 11, the signals from these terminals are applied to the grids of the tubes V1, V2, V3, and V4. These tubes are supplied with a signal on their screens which is generated by means of a local oscillator operating at a frequency of approximately 1 kc. This oscillator and its associated phase-shifting network generates four signals of the same frequency, but the phase relations are such that if one is taken as 0 degree, there will be one at 90 degrees, one at 180 degrees, and one at 270 degrees. The four tubes V1, V2, V3, and V4 with their 1-kc screen supply constitute a switching system in which one tube is active for only about one-fourth of each cycle of the local 1-kc oscillator. The plates of the four tubes are connected together and the primary of a 60-kc band-pass filter serves as the common plate load for the four switching tubes. The output of the band-pass filter is a 60-kc signal so modulated by the 1-kc switching system that if a signal is fed to the grid of only one of the tubes, there will be output from the band-pass filter during only about one-fourth of each cycle of the 1-kc oscillator. The output of the 60-kc band-pass filter is fed to a two-stage resistance-coupled amplifier which in turn is coupled to a third stage with a 60-kc band-pass filter in its plate circuit. The two-stage resistance-coupled amplifier is blanked during the time of transmission by application of the negative pulse from the time base to the suppressor grids in the tubes. These two stages are also subject to AVC control applied to the control grids of the tubes. The method of obtaining the AVC will be described in a later section.

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The third stage of the 60-kc amplifier contains the enabling feature. This stage is biased to cutoff by means of a negative bias applied to the suppressor grid and the control grid so that a signal cannot pass this stage unless a positive enabling pulse is supplied to counteract this bias. The enabling pulse is supplied from the doppler-enabling receiver which will be described in the next section. Following the third stage of 60-kc amplifier is a rectifier which serves as a demodulator. The output of the demodulator contains a filter C1 and R7 which removes the

larity is determined by whether the signal on terminal 2 or 5 of the input circuit is larger. Each of these phase-sensitive detectors has a maximum output voltage which is determined by the level of signal from the 1-kc oscillator. For small values of target angle the voltage output of the phase-sensitive detectors is a function of target angle, but if the target angle is very much more than 1 degree, the voltage level of the phase-sensitive detectors will reach the saturation value. The outputs of the two phase-sensitive detectors are fed to the steering-relay am-

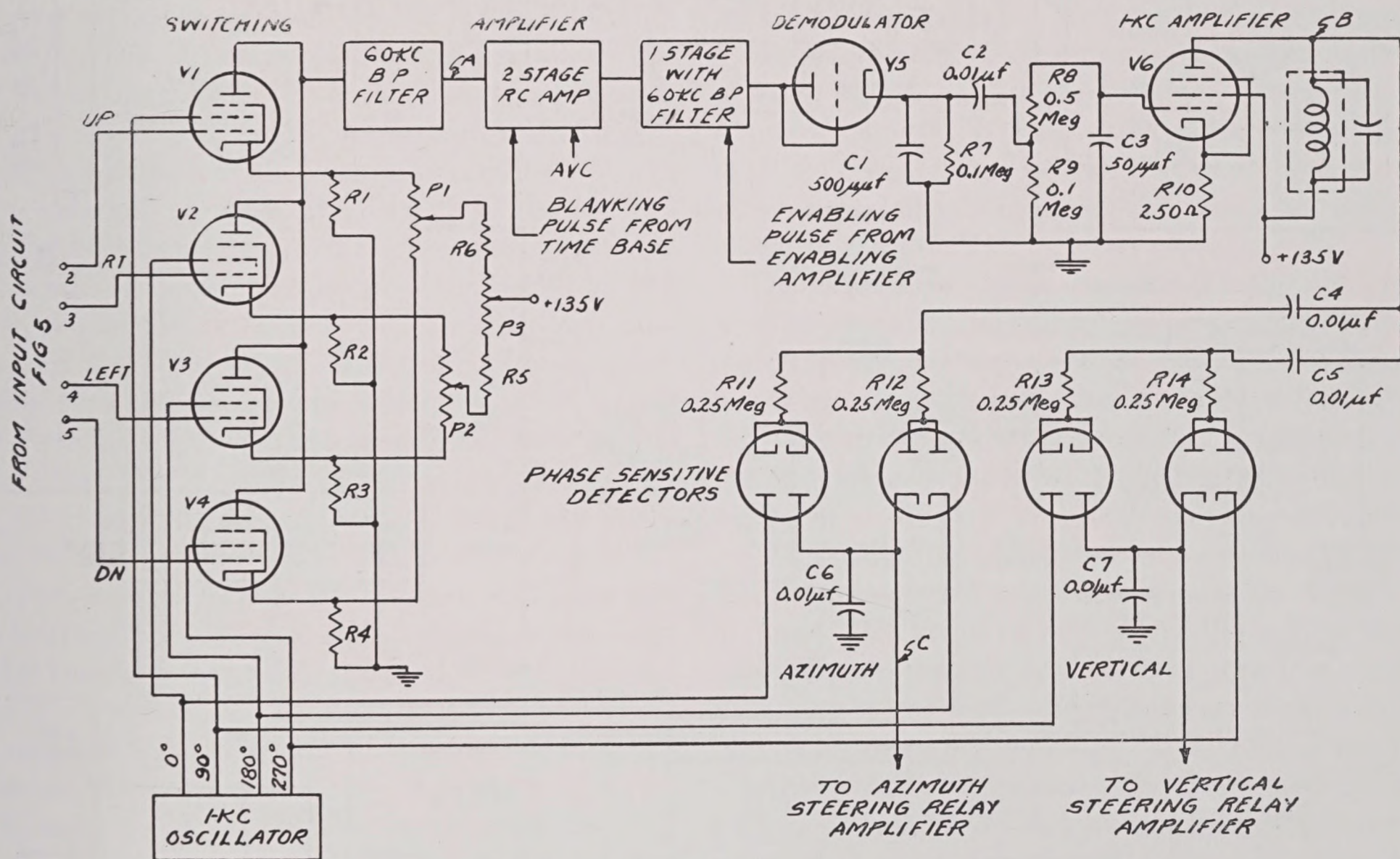


FIGURE 11. Steering receiver.

residual 60-kc signal. The resulting 1-kc signal which also contains considerable 2-kc and 4-kc components is fed to the grid of V6 which is a 1-kc amplifier with tuned plate load of sufficiently high  $Q$  so that the 2-kc and 4-kc components in the signal are quite effectively suppressed. The output of the 1-kc amplifier is fed by means of two  $0.01\text{-}\mu\text{f}$  condensers to two phase-sensitive detectors. These phase-sensitive detectors receive activating signal from the same 1-kc oscillator system which is used for switching the input tubes. In this way the phase-sensitive detector marked azimuth generates a d-c voltage whose polarity is determined by whether the signal on terminal 3 or 4 of the input circuit is larger. The vertical phase-sensitive detector produces a d-c voltage whose po-

larity is determined by whether the signal on terminal 2 or 5 of the input circuit is larger. Each of these phase-sensitive detectors has a maximum output voltage which is determined by the level of signal from the 1-kc oscillator. For small values of target angle the voltage output of the phase-sensitive detectors is a function of target angle, but if the target angle is very much more than 1 degree, the voltage level of the phase-sensitive detectors will reach the saturation value. The outputs of the two phase-sensitive detectors are fed to the steering-relay am-

plifiers. These amplifiers will be described in a later section. The sensitivity of the four switching tubes V1, V2, V3, and V4 to the 60-kc signal is controlled by three potentiometers, P1, P2, and P3, which control the level of direct current which is allowed to flow in the resistors R1, R2, R3, and R4. The voltage drop in these resistors controls the grid bias of these tubes and therefore their sensitivity. It is necessary to provide the three potentiometers in order to balance the sensitivity of V2 and V3 for the azimuth channel and V1 and V4 for the vertical channel and then to balance the vertical channel relative to the azimuth channel.

When an echo with doppler frequency shift is re-

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voltage developed on the four quadrants of the transducer and has the frequency of the received acoustic signal which is nominally 60 kc. V2 is a frequency-converter stage with the signal supplied to its control grid from the output of the stage V1. The signal which is supplied to its screen is the output of the oscillator stage V9 whose frequency is nominally 53 kc. The plate load of V2 is the primary of a 7-kc band-pass filter which has a frequency range of 1.4 kc between the two 3-db down points. This band-pass filter selects the 7-kc frequency difference from the combination of frequencies present in the plate circuit of V2. The two-stage amplifier which follows the 7-kc band-pass filter is the same two-stage amplifier as is indicated in Figure 11. An important feature of this device is the use of a common amplifier for the 60-kc steering receiver and the 7-kc frequency-sensitive receiver. Both of these receivers are under AVC which is applied to this two-stage amplifier; the source of the AVC voltage is the signal voltage generated in the 7-kc channel. Following the two-stage amplifier is a third stage which includes a 7-kc band-pass filter identical with the one in the plate circuit of the stage V2. A portion of the output of this last 7-kc band-pass filter is rectified for use in the automatic volume control which will be described in detail in Section 19.9. Another portion of the output goes to the amplitude gate which passes an echo signal if it exceeds the background level of reverberation by as much as 5 db and persists for as long as 5 msec. The amplitude-gate circuit will be described in detail in Section 19.8.

Since the wave form of the signal emerging from the amplitude gate is considerably distorted, this signal is fed to a 7-kc tuned amplifier which is followed by the stage V3 which contains a discriminator primary in its plate circuit. The stage V3 also serves as a limiter stage so that the discriminator output voltage will be a function of frequency only. The action of the discriminator and the rectifier V4 produces a d-c voltage at A, whose polarity is determined by whether the frequency is above or below the center frequency of the discriminator and whose magnitude is determined by the amount of the frequency difference from the center frequency. The filter consisting of R6, R7, and R8 and the condensers C7, C8, C9, and C10 is an RC filter which is designed to reduce the effect of peaks of voltage at A produced by fluctuations in the reverberation frequency. The discriminator filter has a time constant which adds to the time constant incorporated in the am-

plitude gate, since it is impossible for the discriminator filter to start to build up until after signal has begun to pass the amplitude gate. The time constants of the amplitude gate and of the discriminator filter are important factors to consider in the operation of the entire system, since it is necessary that both of these time constants be overcome before any enabling pulse can be applied to the enabling grids in the last stage of the 60-kc steering amplifier in Figure 11. This enabling pulse must arrive at the enabling grids in the steering amplifier in time to allow the 1-kc amplifier to build up to sufficient voltage to operate the phase-sensitive detectors. It is the sum of all of these time constants which determines the minimum length of transmitted pulse which can be used to operate the system. It was these factors which originally determined the use of transmitted pulses of 30 msec.

The voltage which is supplied at terminal A is used for the automatic frequency control which corrects the local 53-kc oscillator for the own doppler of the torpedo. The relay which is operated by the differentiated negative pulse so that it is closed during the 50-msec interval following transmission is indicated in Figure 12 as the *own-doppler nullifier* [ODN] relay. This relay connects terminal A to the 2- $\mu$ f condenser C15 and the grid 4 of V8. V8 is a reactance tube which serves to place a variable resistance between the condenser C18 and ground. As the potential of the grid 4 of this tube is changed, the effective resistance between C18 and ground is changed; this changes the effective capacitance of C18 in the oscillator tank circuit. The frequency at which the transmitter oscillator is operated is so chosen that with the normal speed of the torpedo, the voltage generated at terminal A by the reverberation signal will be zero when the potential to which the condenser C15 is charged is as near zero as possible. When the torpedo is started, the ODN relay samples the voltage developed at A from the reverberation following each ping and the condenser C15 is gradually charged until the frequency of the 53-kc oscillator is adjusted to the point where reverberation signal produces zero voltage on the average at A. This requires normally from 5 to 10 pulses from the transmitter. The rate of correction of the ODN is determined by the discriminator sensitivity in volts per cycle, the reactance tube sensitivity in cycles per volt, and the resistors R23, R24, and R25, and the condenser C15. The product of discriminator sensitivity and reactance-tube sensitivity is about



100 and the time constant determined by adjusting R25 was made so that when the frequency input at the grid of V1 was shifted 200 c from that which would produce zero voltage at A, four pings would cause the voltage at A to be reduced to half the extreme value; i.e., half correction for the own doppler can be achieved in about four pings. Since the nature of the amplitude gate is such that a continuous signal like the reverberation which is controlling the AVC of the amplifier cannot pass the amplitude gate, it is necessary to disable the AVC during the period of

parallel to the axis of the torpedo. In order to provide for this frequency difference for enablement, a separate 45-v battery in the receiver battery pack was connected to the terminals of R9 and R11 as indicated in Figure 12. The voltage drop across the resistors R10 and R11 provide the voltage which must be overcome by the direct current generated in the discriminator by means of the frequency difference. The value of the required frequency range, called the doppler notch width, can be adjusted by varying the value of the resistor R9.

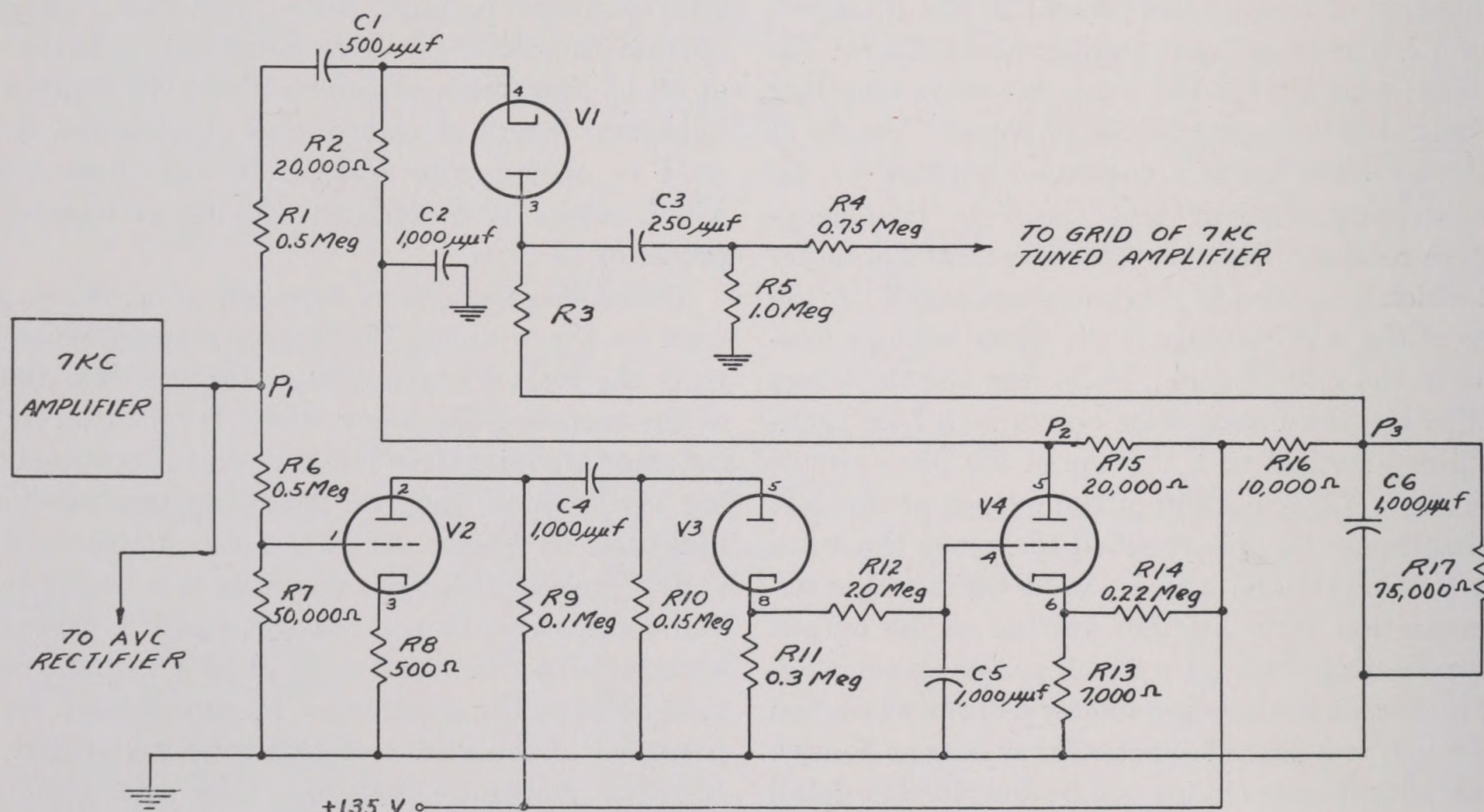


FIGURE 13. Amplitude gate.

sampling of the potential at A by the ODN relay. This is accomplished by another pair of contacts on the ODN relay which perform the function of shorting the AVC during the ODN sampling period.

Since the shape of the pulse envelope emitted by the transmitter produces a certain frequency spread in the transmitted frequency and since all reverberation is not received from points on the axis of the transducer, the reverberation will contain a certain range of frequencies. It is necessary to impose the condition that the doppler shift in frequency caused by the motion of the target be greater than a certain value in order to avoid enabling of the system because of frequency components which are present in the reverberation. The choice of the minimum doppler frequency shift to be used for enablement was about  $\pm 60$  c. This corresponds to a component of target speed relative to the water of  $1\frac{1}{2}$  knots paral-

When the pulses have sufficient doppler frequency shift to produce a voltage which will overcome the bias on either terminal 3 or 8 of V5, the pulse will pass one side or the other of the rectifier and the pulse signal will be applied to the grid 1 of V6. If the pulse supplied to grid 1 is a negative pulse, a positive pulse will be generated at the plate terminal 2 of V6 and will be passed through the lower half of the diode of V7. If, however, the pulse at grid 1 of V6 is a positive pulse, the pulse at plate 2 of V6 will be a negative pulse which cannot pass the diode V7 but a negative pulse will be applied to grid 4 of V6 which will generate a positive pulse at plate 5 which will pass the upper pair of electrodes in V7. The tube V6 therefore plays the role of pulse amplifier and phase inverter so that, regardless of the polarity of the original doppler pulse, a positive enabling pulse will be generated at the output of the rectifier V7. The

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enabling pulse is then applied directly to the suppressor grid and the control grid in the enabling stage of the steering amplifier shown in Figure 11.

## 19.8

## AMPLITUDE GATE

The details of the circuit elements in the amplitude gate are indicated in Figure 13. V1 and V3 are the two sections of a single 6H6 tube while V2 and V4 are the two sections of a single 6SN7 tube. The output of the 7-kc amplifier appears at point P1 in the diagram and this signal is applied via R6 to grid terminal 1 of V2 and via R1 and C1 to the cathode terminal 4 of V1. Terminal 4 of V1 is connected to the point P2 by way of the resistor R2, and the anode,

as happens when an echo is received, will result in a corresponding increase in level of signal at P1. This increase in level of signal at P1 will cause grid terminal 4 of V4 to become more positive, which will change the relative values of the potential at points P2 and P3 so that terminal 3 of the diode section V1 will no longer be negative with respect to terminal 4 of V1. When this condition is achieved, the diode section V1 becomes conducting. The system is so designed that the amplitude gate becomes conducting when the ratio of echo to reverberation level is about 6 db with the level of reverberation at terminal 1 of Figure 5, -90 db referring to 1 v [dbv]. The echo-to-reverberation ratio necessary to pass the amplitude gate increases with decrease in reverberation

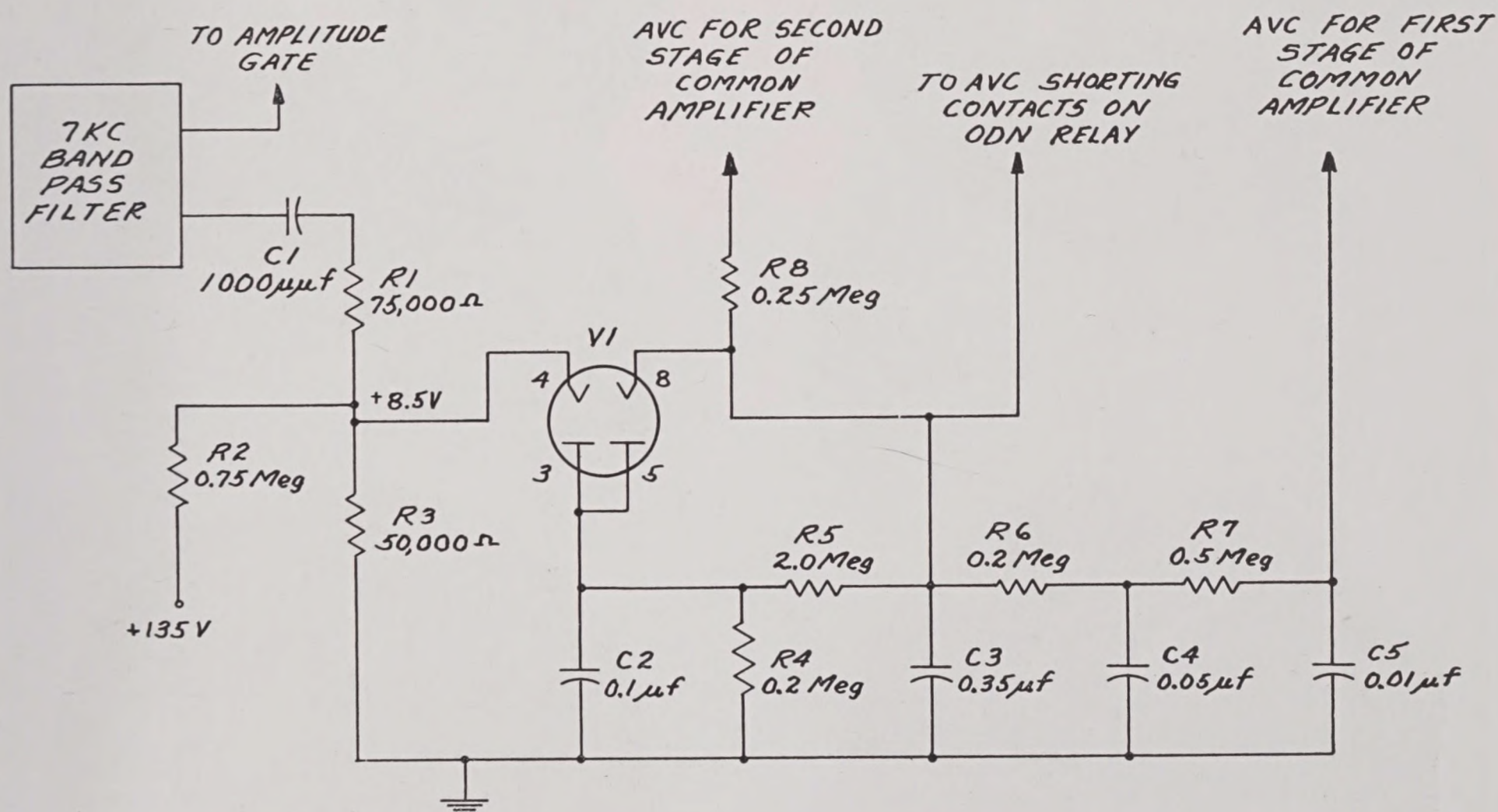


FIGURE 14. AVC circuit.

terminal 3, of V1 is connected to the point P3 by way of a resistor (R3). When no signal appears at P1, P2 is sufficiently positive with respect to P3 so that the diode section V1 cannot conduct any signal. If the signal level at P1 is increased, this signal will be amplified by V2 and the output signal from V2 will be rectified by V3 and the resulting bias applied to grid 4 of V4.

Because of the action of the AVC, the signal level at P1 will remain nearly constant for a considerable variation in the level of the input signal to the amplifier. However, the time constant in the AVC circuit is such that a sudden change in signal level, such

level because the AVC does not provide a perfectly flat response in the common amplifier. The adjustment of the echo-to-reverberation ratio at which conduction takes place is done by adjusting the relative values of the two resistors, R16 and R17. It is also required that the amplitude gate shall remain non-conducting unless the echo signal persists for a period of at least 5 msec. This time constant is obtained by the resistor R12 and the condenser C5. In order to make the amplitude gate conducting during the first 50 msec following transmission, the AVC circuit is grounded by means of a contact on the ODN relay.

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## 19.9

## AVC CIRCUIT

The 7-kc channel is also used as the source of signal for the AVC on the 2 stages of the common amplifier. The tube V1 in Figure 14 is the AVC rec-

which form a bleeder circuit from the +135-v supply, a delay bias of 8.4 v is applied to terminal 4 of the rectifier. When the peak value of the signal exceeds this bias, the diode conducts and charges the condensers C2 and C3. The two-megohm resistor R5

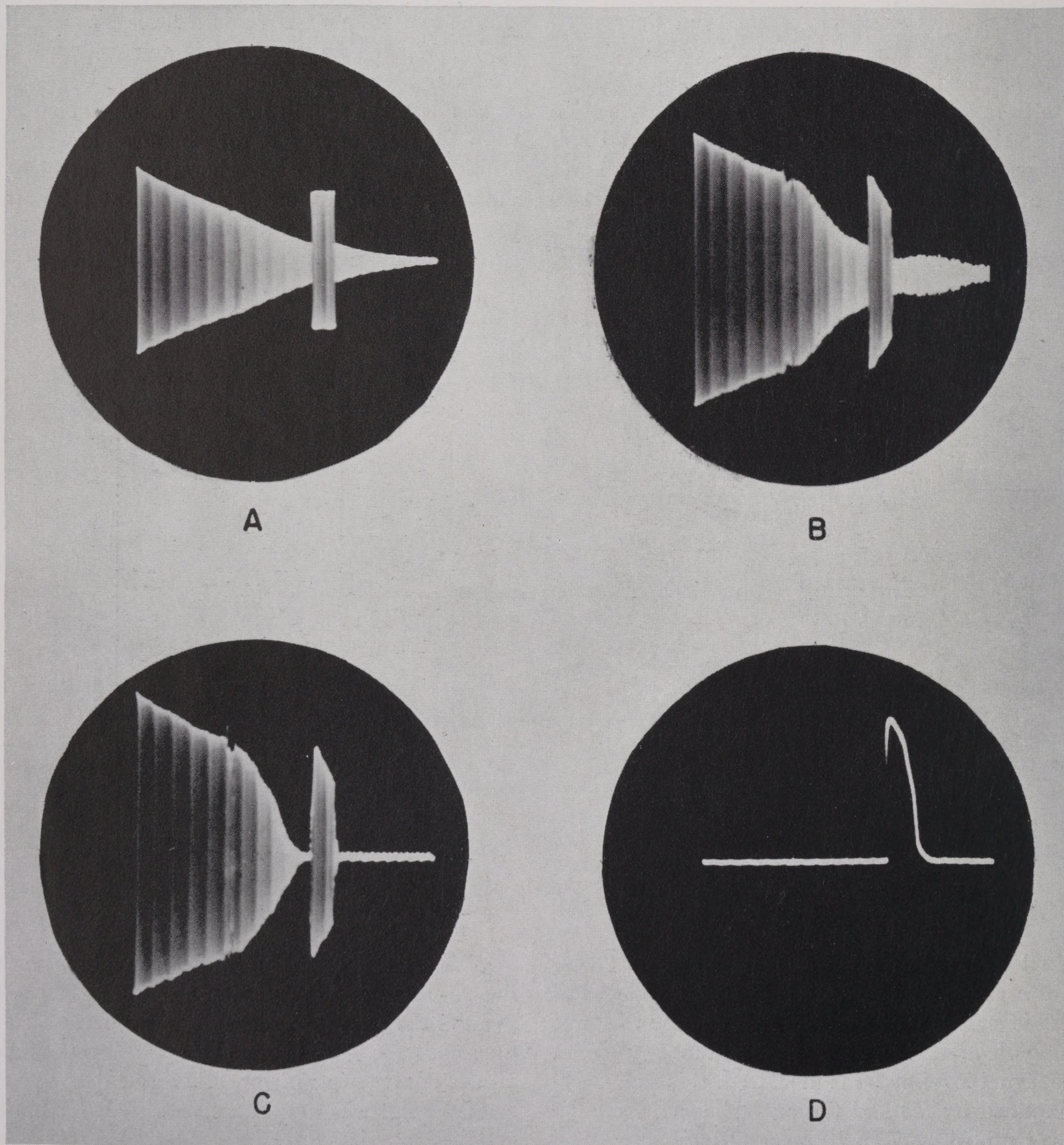


FIGURE 15. Characteristics of the NO181 electronic system.

tifier. The 3-4 section of this tube rectifies the sample of signal which is obtained from the output of the 7-kc amplifier via the condenser C1 and the resistor R1. By means of the resistors R2 and R3

with the capacity of the condenser C3 serve to make the time constant of the AVC system large enough so that an echo signal will not be long enough to control the AVC sufficiently to prevent conduction of



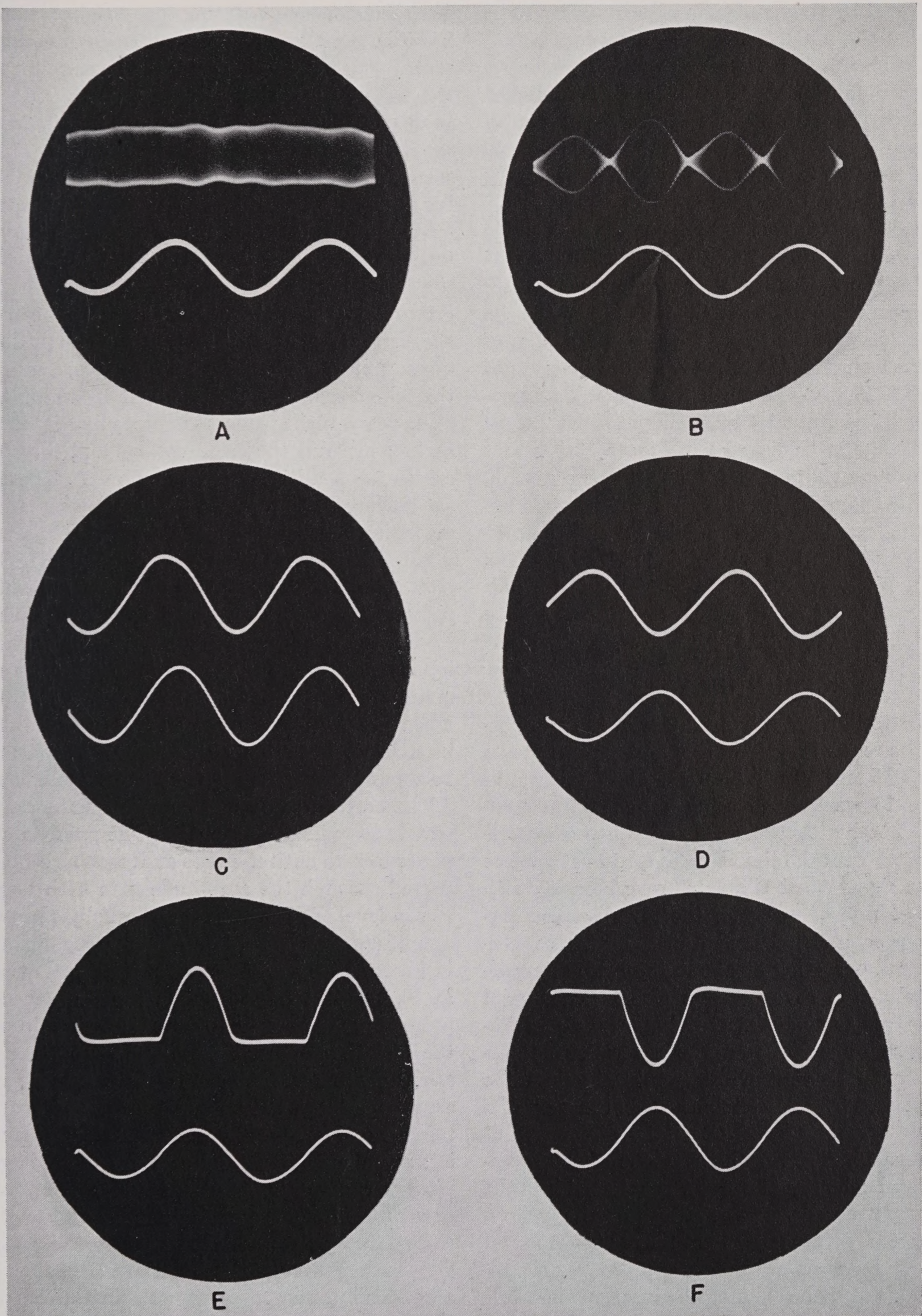


FIGURE 16. Characteristics of the NO181 electronic system.

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the full signal by the amplitude gate. In order to be certain that the AVC action will diminish at a rate sufficient to cause the amplifier to follow the decay in reverberation, the AVC condenser C3 is furnished with a discharge path by way of the 8-5 section of the diode. By this arrangement, the junction of R5 and C3 will never be more negative than terminal 3 of the 3-4 section of the rectifier. The condenser C2 and the resistor R4 serve to take out the 7-kc ripple from the voltage appearing at terminal 3. The AVC voltage for the first stage of the common amplifier is taken from the junction of the resistor R7 and the condenser C5 whereas that for the second stage of the common amplifier is taken from the junction of R5 and C3. The AVC is such that, for a change of signal level at terminal 1 of the input circuit of 20 db, the change in level at P1 in Figure 13 is about 1 db. The removal of the AVC during the first 50 msec of the listening period is accomplished by connecting the junction of the resistor R5 and the condenser C3 to ground by way of one pair of contacts on the ODN relay.

#### 19.10 CHARACTERISTICS OF THE ELECTRONIC SYSTEM

In order to illustrate the behavior of the two portions of the receiver system, the photographs shown in Figures 15 and 16 will be used. The photographs in Figure 15 were made using a *cathode-ray oscilloscope* [CRO] with the sweep of the oscilloscope synchronized with the time base in a test set used to generate a signal which simulated reverberation with the normal rate of decay of the reverberation signal and an echo signal superimposed on the reverberation and occurring at about 180 msec after the beginning of the reverberation signal. The signal generator was so arranged that the echo signal frequency was different from the reverberation frequency by an amount which would simulate the doppler caused by a reasonable speed of motion of a target.

In Figure 15, A shows the envelope of the reverberation and echo signal which was injected into the receiver input circuit. The striations on the pattern are produced by a 60-c pickup in the oscilloscope and serve as a time scale on the pattern. In Figure 15, B was obtained by connecting the input of the oscilloscope to point B in Figure 12. This is a point in the amplifier of the enabling receiver just preceding the amplitude gate. In order for the amplitude gate to pass

reverberation signal during the initial portion of the listening period and to correct the local oscillator for own doppler of the torpedo, it is necessary to short the AVC by means of a contact on the ODN relay. In B of Figure 15 a transient can be observed after the fifth striation on the signal envelope. This transient is produced when the contacts of the ODN relay are opened. It will be noted that the shape of the envelope from the extreme left-hand side up to this transient is similar to the shape of the envelope in the corresponding portion in A. After the AVC short is removed, the AVC rapidly assumes control so that the signal level at this point in the circuit decreases quite rapidly. When the echo arrives, the effect of the echo signal, which is at about 10 db higher level than the reverberation just preceding it, is to still further increase the AVC voltage and therefore decrease the sensitivity of the amplifier. The level of the reverberation signal just following the echo measured at this point in the amplifier is actually lower than it is a few msec later. Figure 15C is the photograph of the envelope of the signal which appears at point C in Figure 12. This is at a point following the amplitude gate. The nature of the envelope of the signal during the time the AVC is shorted is similar to the shape of the envelope in B. However, when the AVC is allowed to function, the signal is brought down to the point where the amplitude gate becomes nonconducting, about 80 msec after the AVC short is removed. The effect of the amplitude gate is to reduce the signal at this point in the amplifier to zero until the echo arrives. The echo is then passed through the amplitude gate with very little loss in level and, as soon as the echo has passed, the amplitude gate becomes nonconducting again. At D in Figure 15 is a photograph of the signal at point D in Figure 12. This signal is the doppler-enabling pulse. It is important to note here that, in spite of the fact the amplitude gate was conducting during about the first 160 msec of the listening interval, the signal which was passing the amplitude gate contained no target doppler and therefore no corresponding signal was generated at point D in Figure 12. However, when the simulated echo arrived, the presence of the frequency shift due to the target doppler caused the pulse indicated at D to be generated. This is the pulse which is used to enable the steering amplifier in order to permit steering information to be developed for the steering relays. It is obvious from this sequence of photographs that two conditions must be satisfied by an echo. First, it is neces-

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sary that the echo have a level above background reverberation in order for the echo signal to pass the amplitude gate. After passing the amplitude gate, it is necessary that this echo signal have a frequency different from that of the background reverberation in order to generate a doppler pulse for enablement of the receiver. The echo-to-reverberation ratio which is required for enablement of the system is 6 db at a reverberation level of  $-90$  dbv on the transducer and the frequency difference between reverberation and echo in order to generate an enabling pulse from the discriminator is 60 c.

In Figure 16 a series of photographs of oscilloscope patterns illustrate the behavior of the steering receiver. These photographs were made using an oscilloscope and electronic switch which made it possible

responded to an echo from a target on the transducer axis, the modulation lobes would be of equal amplitude.

In C and D, of Figure 16, the signal appearing at point B, in Figure 11, which is the output of the 1-kc amplifier, is represented in the upper portion of the photograph. In Figure 16, C shows the signal appearing at this point when the target is to the left of the axis, while D shows the signal at this point when the target is to the right of the axis. It is important to note that the only difference between these two signals is their phase relation relative to the 1-kc reference signal at the bottoms of the photographs.

At E and F the signals appearing at the output of the azimuth phase-sensitive detector, which is point

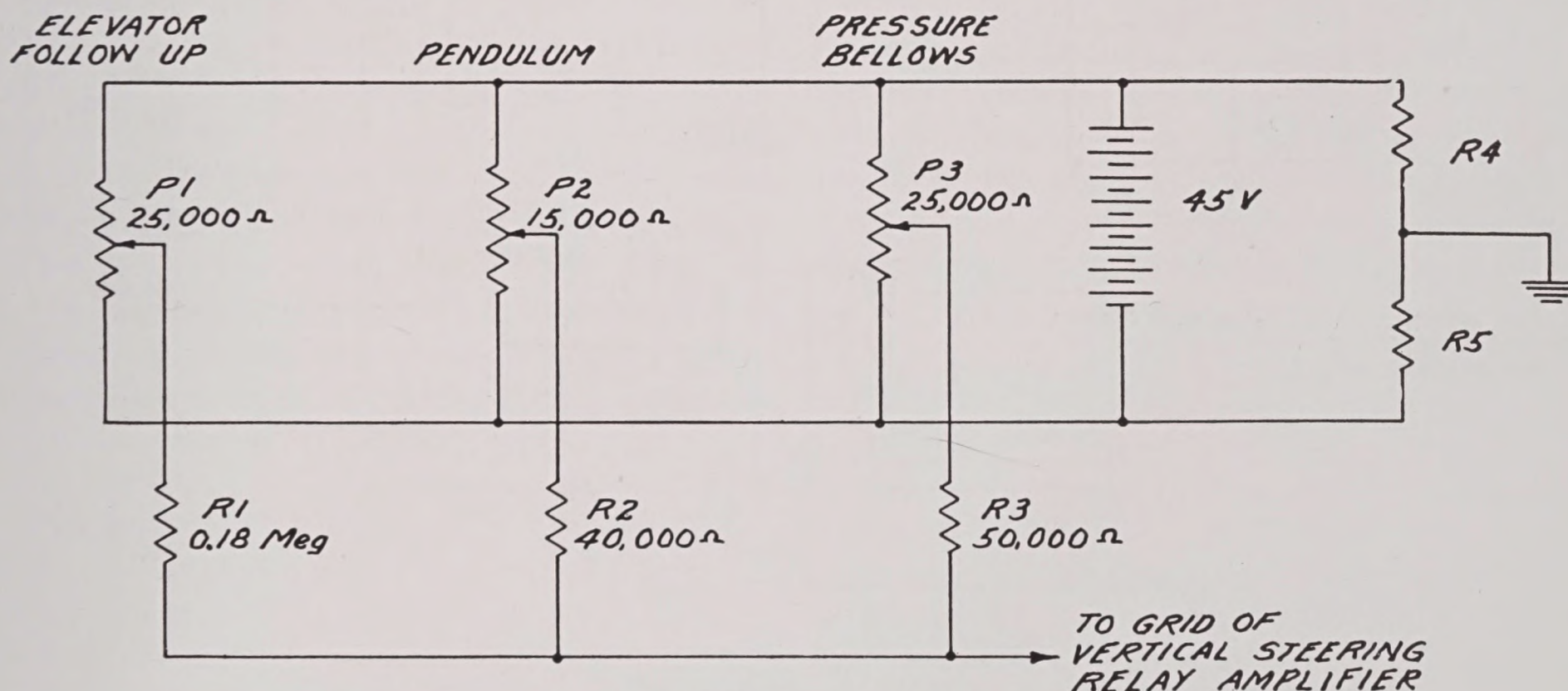


FIGURE 17. Hydrostatic control network.

to present two patterns on the face of a CRO simultaneously. The upper pattern is the pattern produced by the signal which is being studied. The lower pattern is a 1-kc signal obtained from one of the terminals of the 1-kc oscillator in Figure 11. This same reference signal is used in all six of the photographs shown in Figure 16. In A, of Figure 16, the upper signal photograph is an envelope of a signal which occurs at point A, in Figure 11, when the signal injected in the input circuit corresponds to that generated in the transducer when an echo is received from a target on the axis of the transducer. In Figure 16, B shows a photograph of a signal at the same point when the signal is injected only at terminals 3 and 4 in Figure 11 and the signal corresponds to that generated in the transducer by an echo either to the right or left of the axis of the transducer. If the signal cor-

C in Figure 11, are represented. At E the signal corresponds to that produced when the target is to the left of the transducer axis while at F the signal corresponds to that produced when the target is to the right of the transducer axis. In this case the signal is in the form of rectified pulses, the difference being that in one case the pulses are positive, while in the other case the pulses are negative. In normal operation the series of pulses occurring during receipt of an echo are averaged by means of the condenser C6 in Figure 11. For the purpose of making these photographs, C6 was removed from the circuit so that the individual pulses could be observed more readily on the oscilloscope.

When the system is in normal operation the signal indicated at A and B of Figure 16 would appear, regardless of the level relative to background and re-



ardless of frequency difference between the signal and background. However, unless the requirements imposed by the amplitude gate and the doppler gate are met in the enabling channel so that a suitable doppler pulse is generated, the signals indicated in C, D, E, and F of Figure 16 would not be present because the enabling pulse is required in order for the signal to pass the last stage of the 60-kc receiving amplifier.

elevators. The voltage outputs from the centers of these potentiometers are fed to a common point through the resistors R1, R2, and R3. The relative values of these resistors determine the relative importance of the positions of the sliding contacts in the three potentiometers. The common point of the three resistors R1, R2, and R3 is connected to the grid of the amplifier which controls the positioning of the vertical steering relay.

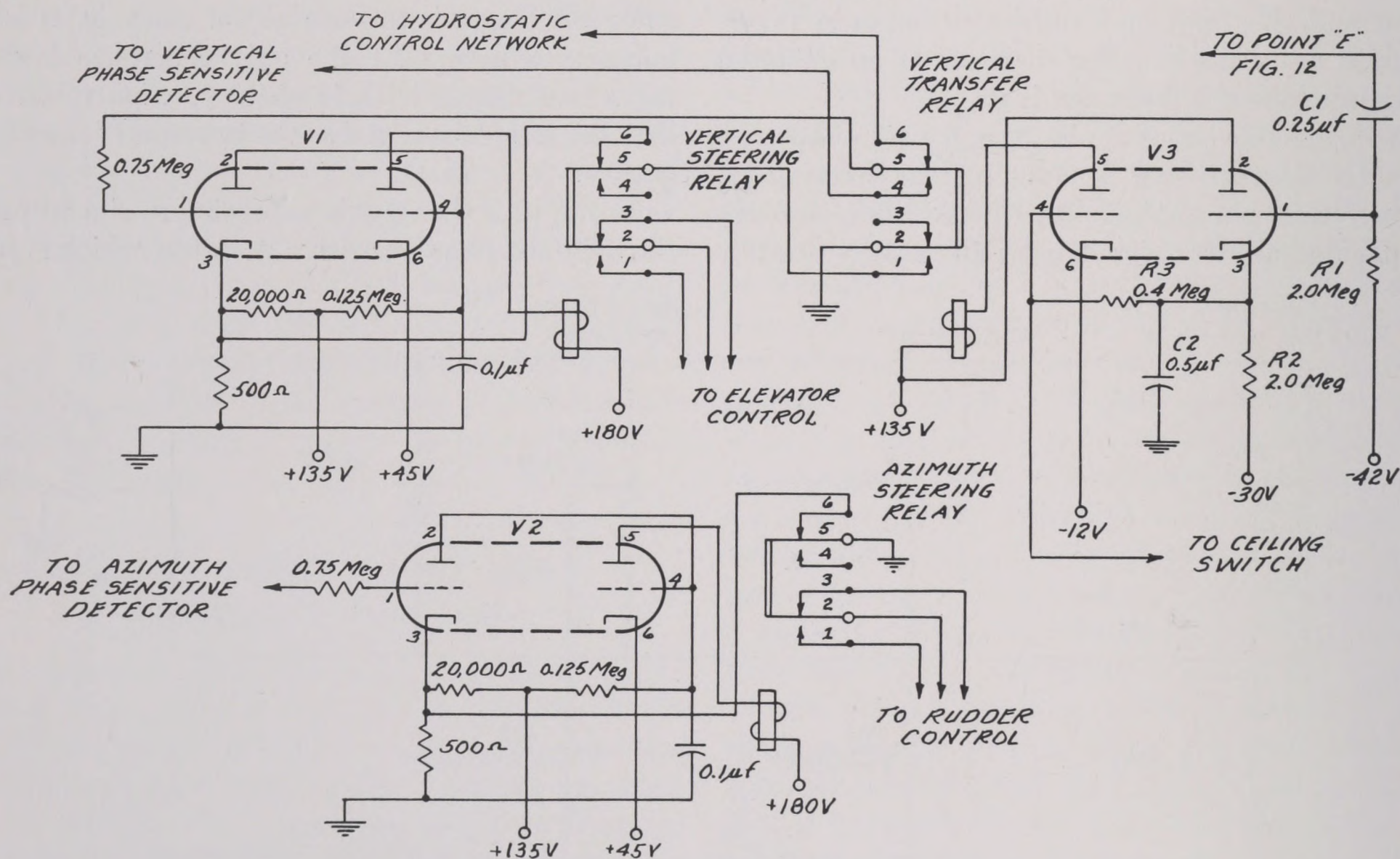


FIGURE 18. Relay circuits.

### 19.11 CONTROL CIRCUITS

There are two control conditions for the torpedo. The first is the search condition where the torpedo circles in the azimuth plane and operates under hydrostatic control at a fixed depth of about 225 ft. The direction of circling in the azimuth plane is determined by the last position of the azimuth steering relay. The hydrostatic control system which controls the depth operation uses the circuit network shown in Figure 17. P1, P2, and P3 are three potentiometers which are connected to the two terminals of a floating 45-v battery. This battery is bridged to ground by the two resistors R4 and R5 so that its center is maintained at ground potential. The potentiometer P3 is operated by the pressure bellows, the potentiometer P2 is operated by the pendulum, whereas the potentiometer P1 is operated by the

When an acoustic signal is received on the transducer which satisfies the conditions for generating a pulse out of the enabling amplifier at point E in Figure 12, this pulse voltage is applied to grid terminal 1 of V3 in Figure 18. V3 is an amplifier which controls a relay called the vertical transfer relay. The amplifier is a two-stage direct-coupled amplifier in which the first stage is used as a cathode follower and a time constant is introduced in the output of this stage by means of the resistor R2 and the condenser C2 so that when a signal is received on the grid terminal 1, the voltage generated on grid 4 will be held sufficiently long so that the relay will remain closed for about 3 sec. The contact 5 on this relay is connected through a 750,000-ohm resistor to grid terminal 1 of V1 which is the vertical steering relay amplifier. Contact 6 on the vertical transfer relay connects to the common terminal of R1, R2, and R3



in Figure 17. When the vertical transfer relay is open, which is true in the absence of echoes from a target, the grid of V1 is connected to the output of the hydrostatic control network which will then control the positioning of the vertical steering relay through the amplifier V1. When an echo is received from a target, the vertical transfer relay closes and contact 5 is connected to contact 4 which connects the grid 1 of V1 to the vertical phase-sensitive detector.

When the torpedo is under acoustic control, the steering information arrives intermittently, so that it is necessary that the steering relays hold in the position indicated by the last received echo until an echo arrives which indicates that the position should be changed. This means that under acoustic-steering conditions, the steering-relay amplifiers must have a holding feature. This feature is accomplished by means of contacts 5 and 6 on both the vertical and azimuth steering relays. When the vertical steering relay is in the open position, contact 6 is connected to contact 5 which in turn is connected to ground through contacts 1 and 2 of the vertical transfer relay. This means that when the steering relays are open, the cathodes 3 of the steering amplifiers are at zero potential relative to ground. When the relays are closed, however, the cathodes 3 of the steering

relay amplifiers will be at a positive potential. This arrangement provides the holding feature for these relays. The holding feature for the vertical steering-relay amplifier operates only when the vertical transfer relay is closed. The rather long holding time for the vertical transfer relay causes the system to steer in the direction of the last-received echo in the vertical plane for about 3 sec after the last echo of a series is received. If no echoes are received during this interval, the vertical transfer relay drops open and the vertical steering relay is connected back to the hydrostatic control network which steers the torpedo back to the original operating depth. The contacts 1, 2, and 3 on both of the steering relays are the rudder control contacts. Contact 2 on each of these relays connects to the 36-v terminal of the main motor running battery. Contacts 1 and 3 each connect to one terminal of a field winding in the steering motors which are provided with double field windings in order to make them reversible. By means of the holding feature in the steering relay systems the voltage required to change the relay from the closed to the open position or from the open to the closed position is about 2 v.<sup>a</sup>

<sup>a</sup> See references 1-3, 6, 14, 17, 20-27, 29-36, 38-44, and 62 for additional material on topics in this chapter.



## Chapter 20

### THE BRITISH DEALER SYSTEM

THIS device was developed on a program corresponding to the NO181 program in this country. It was designed as an aircraft-launched, echo-ranging torpedo to be used against submarines with the gear mounted in a body 7 ft 4 in. long, 18-in. diameter, and weighing 590 lb. The operating speed is 12 knots with an operating time of 15 minutes.

timing the transmitter, also applies the *time-varied gain* [TVG] voltage to the receiver and operates two sets of selector switches which permits the information for depth steering and azimuth steering to be taken from alternate pulses. The receiver is a two-channel amplifier followed by a phase-sensitive detector for comparing the phase of the signals sup-

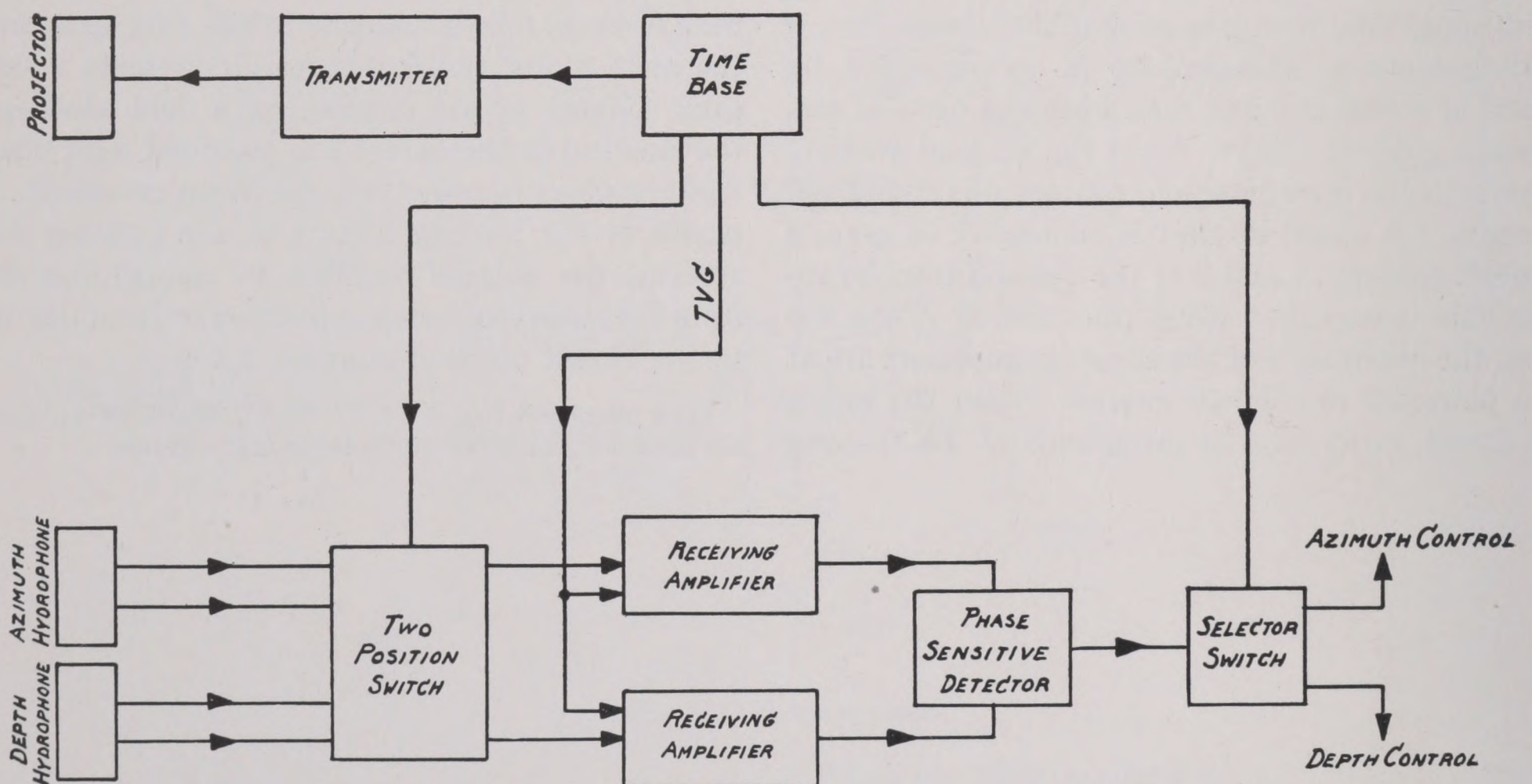


FIGURE 1. Block diagram of the British Dealer system.

The transducers and explosives are mounted in the head, the body contains the electronic gear, and the battery is mounted in the after section. A block diagram of the control is shown in Figure 1.

The transducer assembly consists of two units: the first serves as the projector and the second as the receiver. The receiver section is divided into two portions, one for azimuth reception and the other for depth reception. The beam pattern is broader in azimuth than in depth. The transmitter, consisting of an oscillator driving a power amplifier, is actuated by a cam-operated time base which, in addition to

plied by the two amplifiers. By means of the above-mentioned selector switches in the time base, steering in both azimuth and depth is permitted. Azimuth steering is accomplished by varying the relative speeds of two propellers which are operated by two separate propulsion motors. Depth steering is accomplished by sliding the main running battery backward and forward on a set of rails by means of a motor-driven screw. The search plan is a descending helix of 50-yd radius.<sup>a</sup>

<sup>a</sup> See reference 66 for additional material on topics in this chapter.



## Chapter 21

# ORDNANCE RESEARCH LABORATORY PROJECT 4 SYSTEM

### 21.1

### INTRODUCTION

THE results of experience with the Harvard Underwater Sound Laboratory [HUSL] device operating against echo repeaters and submarines indicated the desirability of making the following modifications.

1. The use of separate amplifiers for the enabling system and the steering amplifier.
2. The use of *time-varied gain* [TVG] either in addition to or in place of *automatic volume control* [AVC].
3. A change in the method of securing the doppler notch from a circuit using a battery with no ground reference to an arrangement operating from a source of potential grounded at one end.
4. Substitution of glide-angle control in the vertical plane for the on-off vertical steering.

The features of the system which had proved especially valuable and were retained are:

1. The transducer and input circuit which permits transmission and reception with the same transducer without switching.
2. The use of the quadrature-switching system and phase-sensitive detectors making possible the handling of steering information for two-plane steering in a single amplifier.
3. The doppler-enabling system which effectively prevents steering on echoes reflected from the surface and from target wakes. It also allows use of a higher receiver sensitivity without danger of steering on bursts of reverberation.

When the program on torpedo control was moved to the Ordnance Research Laboratory [ORL], a research program was set up to develop a new system employing all the advantages of the Harvard NO181 system but incorporating such modifications as the experience gained in the Harvard NO181 program indicated as desirable. At the same time it seemed desirable to develop this device as an anti surface-ship torpedo. Since there was no assignment to incorporate the system into any specific existing torpedo, the Mark 18 was chosen as a convenient one for the

purpose of the necessary investigations. The first investigation in this program used a Mark 18 torpedo equipped with a newly designed transmitter capable of generating 1,500 watts of electric power and a receiving system so set up that the self-noise level, the reverberation level, and the frequency spread in the reverberation could be measured. This device was designed purely as a research torpedo, with no intention of applying acoustic steering control to it. Since the Mark 18 torpedo is gyro-controlled and the beam pattern of the transducer is very narrow, a new system of azimuth search was incorporated. In order to make it possible for the torpedo to scan a relatively large angle, a special cam plate was made for the gyro with the cams placed 60 degrees apart. This causes the torpedo to operate on a snaky course such that the axis of the torpedo swings from 30 degrees on one side of the set course to 30 degrees on the other side. Tests run on the dynamics of this system at the Newport Torpedo Station indicated that the reduction in forward progress caused by the use of the  $\pm 30$ -degree snaky course amounted to a little over 5 per cent. At the time of writing, the data are not complete on the reverberation level and the frequency spread in the reverberation. However, the self noise of the torpedo has been measured at an operating speed of 20 knots. The value is about 5 db which corresponds to a signal of  $-127$  db referring to 1 v [dbv] on the transducer when the receiving band width is 4 kc. When these data are complete for a series of torpedo speeds, it will be possible to determine the minimum component of target speed parallel to the axis of the torpedo which will need to be used for enabling of the steering amplifier at each torpedo speed.

Figure 1 shows a block diagram of the overall system as worked out for project 4G. In this case the steering amplifier is completely independent of the enabling amplifier except for the enabling signal which is supplied to enable the demodulator. The amplitude gate is no longer included as part of the doppler-enabling system since this former arrangement caused the time constant of the amplitude gate to be added to the time constants of the discrimina-



tor filter. The amplitude gate is incorporated as part of the steering amplifier and is actuated by the signal present in the steering amplifier circuit. In order to enable the system, it is necessary for a pulse to be developed out of the enabling amplifier at the same time that a pulse is developed in the steering amplifier which can give rise to an amplitude gate pulse.

transformer through a 0.01- $\mu$ f condenser instead of to one end of the low-impedance winding.

### 21.3

### TIME BASE

The time base employed in this system is a set of four cam-operated switches. The cams for these switches are mounted on a single shaft which is

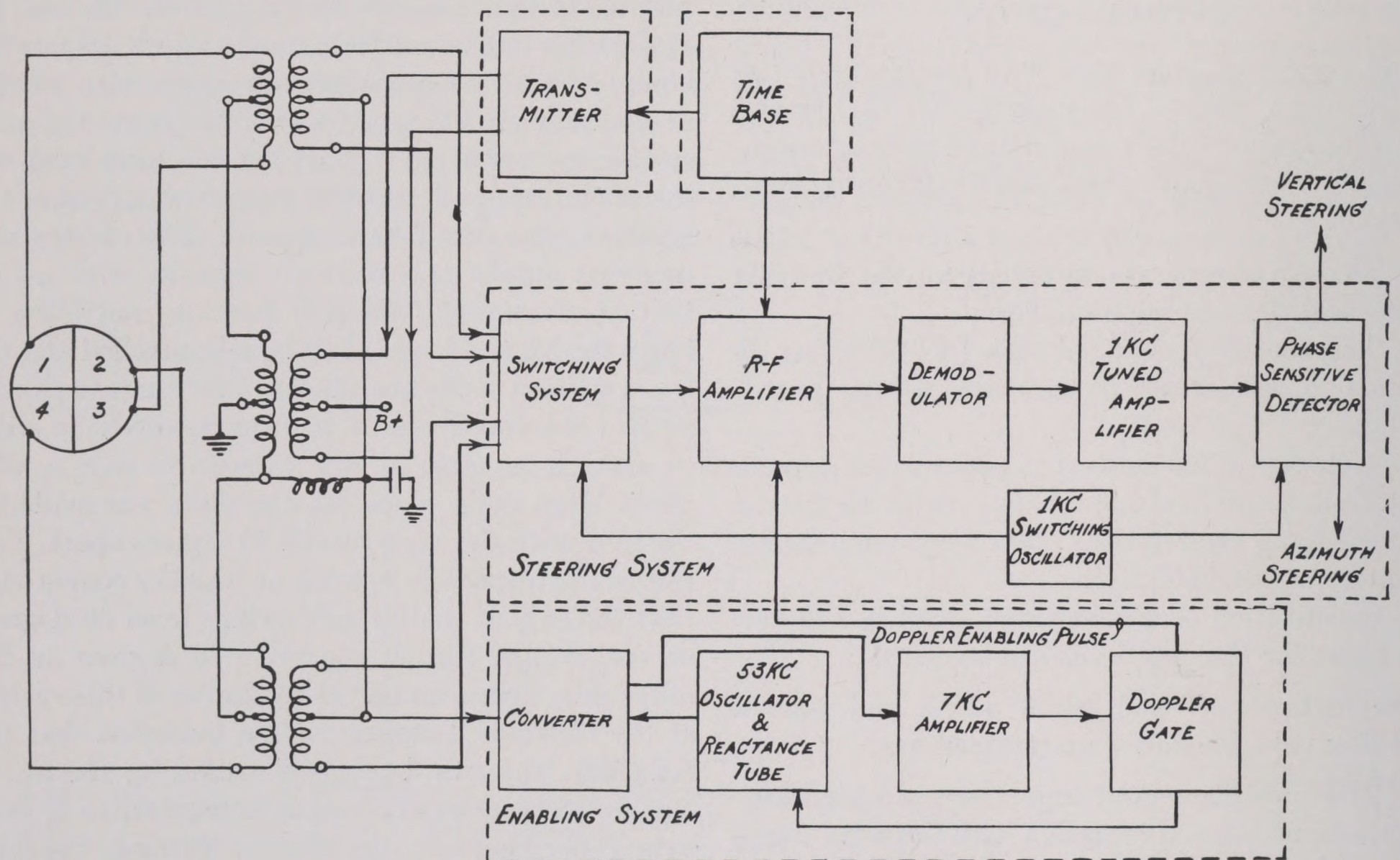


FIGURE 1. Block diagram of ORL project 4 system.

### 21.2 TRANSDUCER AND INPUT CIRCUIT

The transducer used is the same as that used in the Harvard NO181 system. Figure 4, Chapter 19, shows the pattern characteristics of a typical transducer when high power is generated in the transmitter. These transducers have been used with a high-power transmitter over quite long periods and, although they are eventually reduced in sensitivity because of depolarization of the magnets, the life of the transducer is adequate for all practical purposes.

The input circuit is nearly identical with that used in the Harvard NO181 system shown in Figure 5, Chapter 19. The only change is in the turns ratio of the input transformers, making it possible to obtain a voltage step-up of 30 db instead of the original 20 db, and the 90-degree line is connected to a 1/4 tap on the high-impedance winding of the transmitter

driven by the torpedo propulsion motor. Two of the cams operate the transmitter, the receiver blanking and the receiver TVG; one is used to operate the *own-doppler nullifier* [ODN] relay and one is used as a range-measuring cam to control the range at which vertical steering takes place. Figure 2 shows schematically the sequence of events controlled by the time base.

### 21.4

### TRANSMITTER

The schematic of the transmitter circuit is shown in Figure 3. V1 is a 6SN7 tube, one-half of which is used as the transmitter oscillator and the other half of which is used as a buffer stage. The frequency-determining element in the oscillator system is the inductance L1 and the condensers C1 and C2. V2 is a 6SN7 tube used as a push-pull amplifier to drive the grids of the driver stage V3. The grids of V2 are driven 180 degrees out of phase with each other by

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means of the toroidal coil L2. V3, V4, and V5 are all 829B power tubes. V3 serves as the driver stage, V4 and V5 serve as the power output stage. The transformer T1 is the driver transformer used to match

delivers 1,500 v direct current to charge a bank of condensers. The charged condensers serve to supply the 1,500 v at the center tap of T2 and 750 v for the screen supply for V4 and V5 as well as the plate

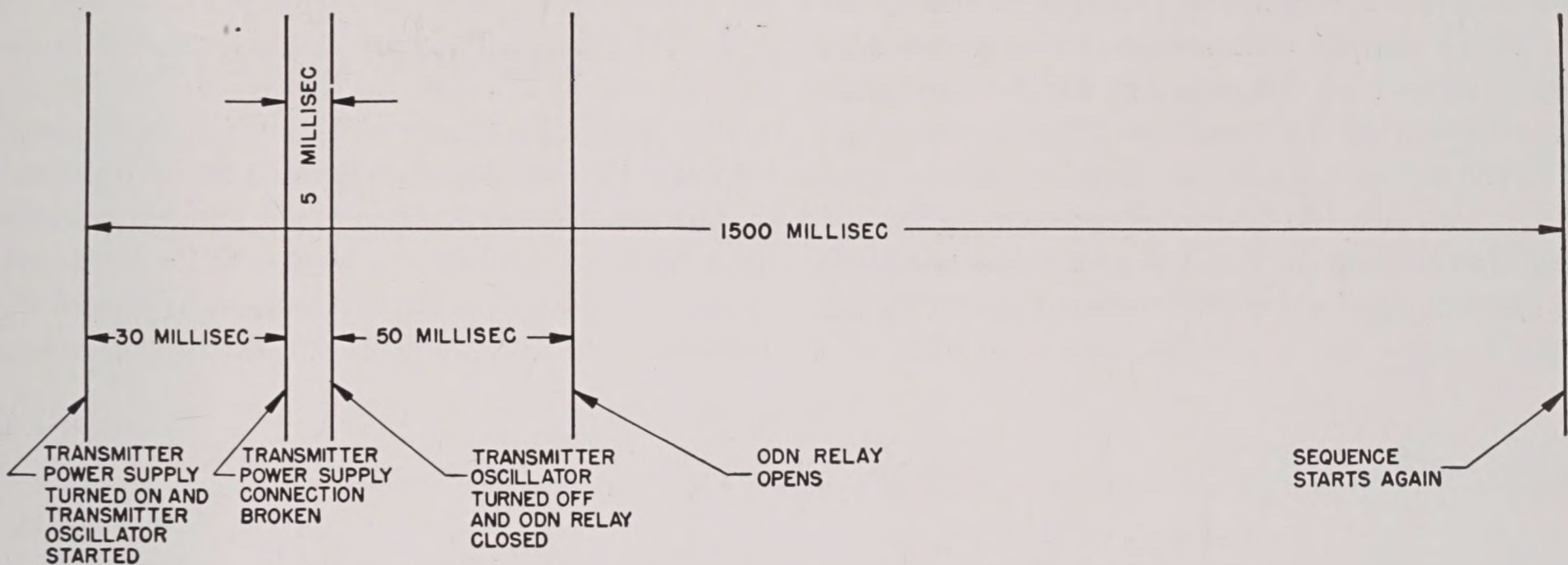


FIGURE 2. Sequence of operations in the time base.

the plate circuits of V3 to the grid input of V4 and V5. This transformer is identical with the transformer T2 which is the power-output transformer which forms a part of the input circuit. (See Figure

and screen supply for V3. The schematic of the transmitter power supply is shown in Figure 4. The condenser C1 is a storage condenser of 80- $\mu$ f capacitance which supplies the high plate current for the

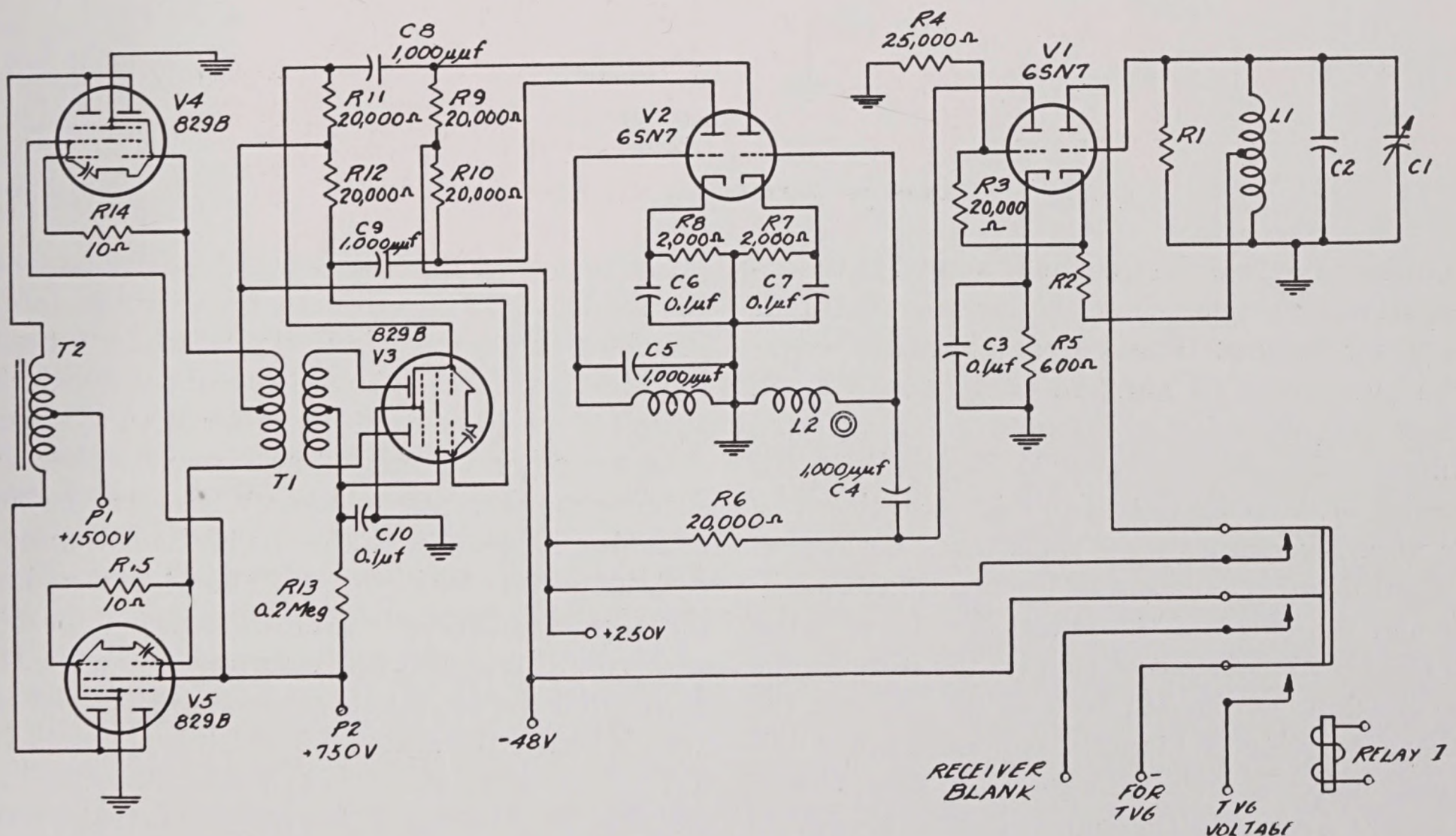


FIGURE 3. Transmitter.

5, Chapter 19.) The plate supply for V1 and V2 is taken from the receiver power supply which consists of a 48- to 300-v motor-generator. The power supply for V3 and V4 is a special motor generator which

plate circuit of the transmitter during the 30-msec transmission interval. During the listening interval C1 is charged from the 1,500-v d-c generator through the resistor R1 which prevents an excessive load be-

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ing thrown on the generator during and immediately following transmission.

The relay in Figure 3 and the relay in Figure 4 are operated by cam switches in the time base. The relay in Figure 4 completes the circuit for the transmitter power supply and actuates the plates and screens of V3 and V4. The relay in Figure 3 actuates the plate circuit of the oscillator by connecting the plate to the power supply. In addition, the relay in Figure 3 connects the blanking voltage to the r-f amplifier in the steering receiver and it also connects the proper voltage to the TVG control circuit in the receiver.

stant during the interval of the pulse. Except for the rounding of the corners of the pulse envelope at the beginning and end of the pulse, the major portion of the top of the pulse envelope is nearly flat.

## 21.5

## STEERING RECEIVER

The steering receiver used in this device is quite similar to that used in the Harvard NO181 system and is shown in Figure 5. The same four-channel switching system controlled by a local 1-kc oscillator generating signals with relative phase relations of 0, 90, 180, and 270 degrees is used. Because of some im-

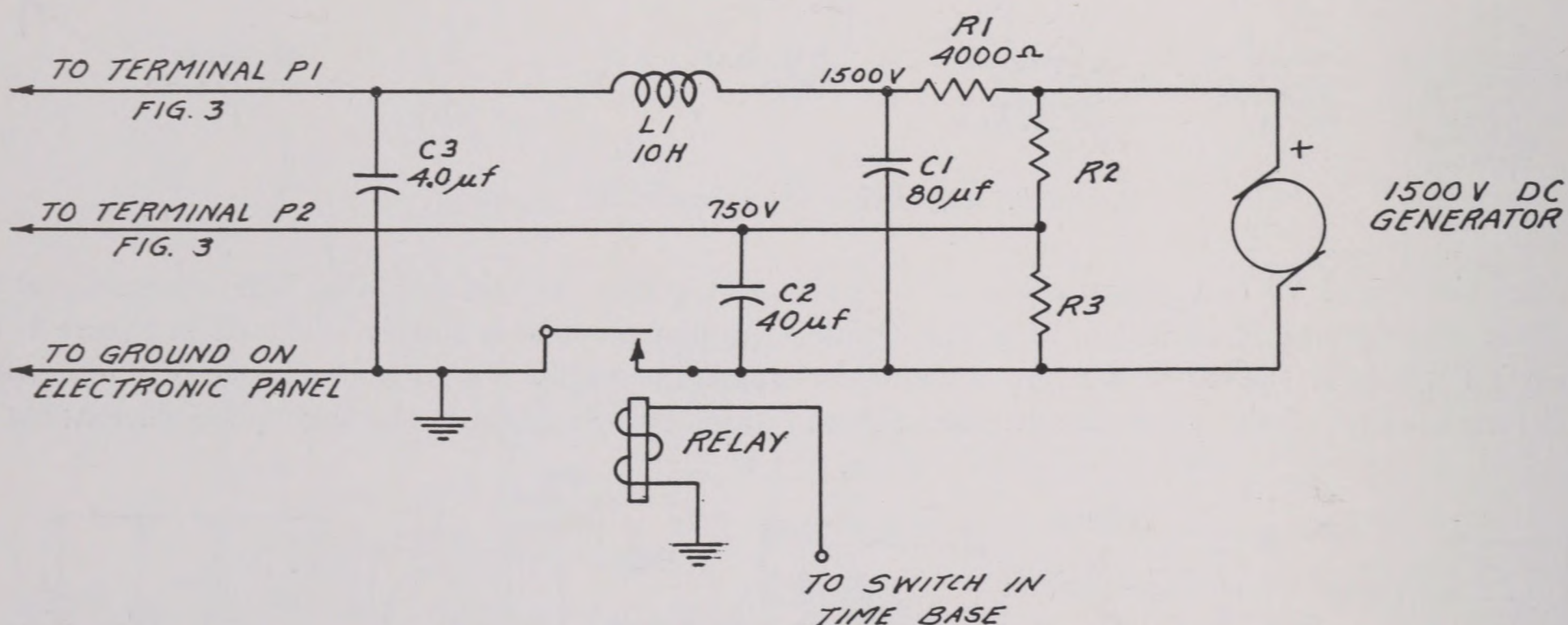


FIGURE 4. Transmitter power supply and pulse-tailoring circuit.

In order to reduce the frequency spread in the reverberation, some pulse-shaping is incorporated in the transmitter system. This is accomplished by means of the inductance L1 and the capacitance C3 and the fact that the relay in Figure 3 is not operated simultaneously with the relay in Figure 4. At the beginning of the pulse these two relays are closed by their respective cams at the same time. Because of the slight delay in build-up of the transmitter oscillator and the effect of the inductance L1 in series with the transmitter power supply, the front of the pulse envelope is rounded both at the top and the bottom. The relay in Figure 4 is opened a few milliseconds before the relay in Figure 3 so that the 4- $\mu$ f condenser C3 serves as the source of power to operate the transmitter during a short interval. This causes the output of the transmitter to gradually decrease, and it is finally stopped when the relay in Figure 3 opens, stopping the transmitter oscillator. In addition, the inductance L1 in Figure 4 helps to make the power output of the transmitter more nearly con-

provement in design of the band-pass filter and a change from 6SG7 tubes to 6AK5 tubes for the switching tubes, the gain in the switching tubes has been increased from about 12 to about 30 db. The output of the 60-kc band-pass filter is fed to the two-stage amplifier V1 and V2 in Figure 5. V1 is a resistance-coupled stage whereas V2 has a 60-kc band-pass filter identical with the one in the output of the switching tubes for its output. The 60-kc signal with the 1-kc modulation is fed to the demodulator V3 which is a grid-controlled rectifier. The enabling pulse from the amplitude gate and the doppler gate are applied to the grid of V3 which is maintained at a d-c potential of about -22 v relative to the cathode. The 22-v bias on V3 is sufficient to make it non-conducting for any signal from the 60-kc channel. However, the pulse which is supplied from the doppler pulse amplifier, when added to the pulse supplied from the amplitude gate pulse amplifier, is sufficient to overcome this bias on receipt of an echo of the proper level and having the proper frequency



difference from that of the reverberation to satisfy the criteria set up in the enabling receiver.

In the Harvard NO181 device the amplitude gate was incorporated in the enabling receiver so that the time constant of the amplitude gate circuit had to be overcome before a signal could be applied to the discriminator driver. The time constant of the amplitude gate and the time constant in the filter of the discriminator were, therefore, cascaded. In this system the amplitude gate is operated by the signal in the 60-kc channel so that the time constant of the amplitude gate has no effect on the time of appearance of a pulse from the doppler enabling channel.

the AVC is to prevent the device from steering on noise countermeasures, since it is possible for the noise countermeasure to generate enabling signal from both the doppler gate and the amplitude gate.

Figure 6 shows the TVG-AVC and the blanking arrangements for the receiver. When the switch in the time base operates the relay in the transmitter indicated in Figure 3, two of these contacts in the relay supply voltages which are introduced in the TVG-AVC circuit of Figure 6 at the points labeled blanking voltage and TVG voltage. The blanking voltage used is  $-48$  v which is the d-c voltage available from the power supply for operation of the fila-

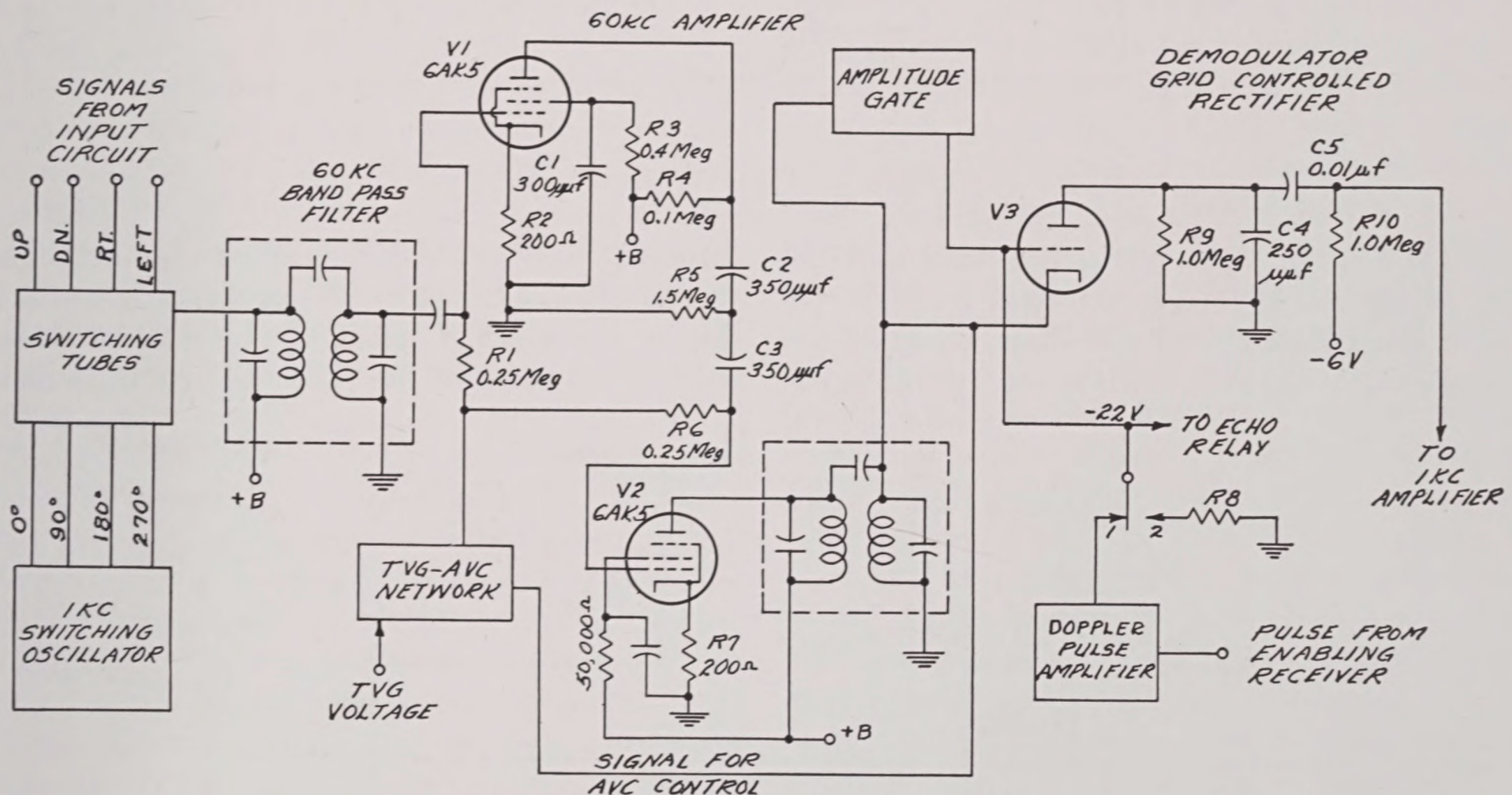


FIGURE 5. 60-kc steering amplifier and demodulator.

Operation data obtained with the Harvard NO181 system indicated that, under some conditions of operation, the AVC control of amplifier sensitivity was not sufficient. To correct this defect, the sensitivity control of the stages V1 and V2 in the 60-kc amplifier is furnished by a combination of TVG and AVC, so arranged that the AVC control can be eliminated by means of a switch. An important characteristic of a doppler-controlled device is the fact that the requirements of the sensitivity control system are not so rigorous as they are with a device which does not have the doppler-enabling feature. It is therefore possible to design the TVG control for operating conditions where the reverberation levels are a minimum and even without the use of AVC the reverberation will not cause false steering. The purpose of

ments and solenoids in the system. The TVG voltage which will be applied to the terminal in Figure 6 labeled TVG voltage is a lower negative voltage, the optimum value of which has not yet been determined, but a value in the neighborhood of  $-10$  volts will be used. During the time of the transmitted pulse a small current flow will take place through R1 because of the difference in voltage impressed at its two ends. However, the condenser C1 will be charged to the potential of the TVG voltage and the grids of the 60-kc amplifier will be maintained at  $-48$  v during the transmission interval. Following transmission, the grids will very quickly take the potential to which C1 is charged, and if the switch S is placed in the 1 position, the condenser will discharge through the 1.2-megohm resistor R2. It is the dis-

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The time constant of the C1, R3, R4 network is between 4 and 5 sec so that a 60-kc signal of very high level would be necessary to produce any appreciable charging of the condenser C1 by way of the AVC network during a normal listening interval.

Figure 7 shows the details of the entire amplitude gate circuit and the pulse amplifier for the doppler enabling pulse. V1 is a 6SN7 tube, the 1-2-3 section of which is used to rectify a signal from the output of the 60-kc amplifier. The rectified signal is fed to the grid of the 4-5-6 section which serves as a d-c amplifier of the rectified voltage output of the 1-2-3 section. It is important to note that there is no condenser coupling between the rectifier and the d-c amplifier. This means that the output of the d-c amplifier will be the same whether the signal supplied from the 60-kc channel is a steady signal or a pulse. The resistor R4 is the plate load resistor for the pulse amplifier portion of V1. The point P1 between R5 and R7 is maintained at a definite d-c potential in the absence of signal from the 60-kc amplifier which is determined by the fact that R1, R2, R3, and R7 are all returned to  $-48$  v and R4 is returned to the  $+250$ -v power supply.

The 1-2-3 section of V2 is a grid-controlled rectifier which serves as the demodulator of the 60-kc signal which is applied to the cathode terminal 3. The d-c potential at the point P1 contributes to the negative bias maintained on terminal 1, the grid of the demodulator. The negative bias maintained on terminal 1 of the demodulator in the absence of signal is  $-22$  v which is determined by the potentials of the points P1 and P2. This negative bias on the demodulator is sufficient to prevent passage of any signal arriving in the 60-kc channel. When a signal is received in the 60-kc channel, the potential of P1 is made more positive because of the action of V1. If the 60-kc signal is a steady-noise signal the effect which it will have at P1 will depend on whether the switch in the TVG-AVC circuit of Figure 6 is set in the 1 or the 2 position. If it is set in the 2 position and steady continuous noise is received, the AVC action will prevent the rise of signal in the 60-kc amplifier to sufficient level to bring the demodulator near to the point of conducting. When an echo is received with the receiver under normal TVG control, the echo will have a level such that a pulse of voltage of a duration equal to the length of the echo will be produced at P1. This pulse of voltage will be sufficient to overcome a part of the  $-22$ -v bias on terminal 1 of V2. If the echo is from a moving target,

a pulse will be generated from the enabling amplifier which will be amplified in the 4-5-6 section of V2 and this pulse voltage, added to that generated at P1, will be sufficient to overcome the bias on terminal 1 of the demodulator. The voltage capabilities of the two pulse amplifiers, the 4-5-6 sections of V1 and V2, are such that one alone cannot generate a sufficient voltage to overcome the full bias on the demodulator grid. It is therefore necessary that a pulse be generated in the enabling amplifier as well as in the 60-kc steering amplifier in order to overcome the bias on the demodulator. This arrangement achieves the criterion of requiring an amplitude pulse and a frequency difference between the received pulse signal and the reverberation in order to enable the system. If it is desired to operate the system as a noise-steering device, the switch *S* in Figure 7 can be turned to the 2 position. This results in eliminating connection to the doppler-enabling channel and at the same time, by proper selection of R13, lowers the bias on the grid of the demodulator to a value which can be overcome by the potential developed at P1 due to a noise signal.

Figure 8 shows the schematic of the 1-kc amplifier and the two phase-sensitive detectors. The 1-kc amplifier uses a tuned plate load and is identical with the one used in the Harvard NO181 system. The phase-sensitive detectors have been simplified somewhat from the original Harvard NO181 arrangement. The new arrangement uses only one double diode for each phase-sensitive detector instead of two. The output of the 1-kc amplifier is connected to the phase-sensitive detectors through the condensers C1 and C2 and the resistors R1, R2, R5, and R7. The activating signals from the 1-kc switching oscillator, which is the same oscillator indicated in Figure 5, are fed to the phase-sensitive detectors through the resistors R3, R4, R6, and R8. The output of the phase-sensitive detector V2 is a d-c voltage which compares the signal input on the terminals marked UP and DN in Figure 5. If the signal on UP is larger in magnitude than that on DN, the d-c voltage appearing on terminals 5 and 7 of V2 will be positive, or if the signal on terminal DN is larger than the signal on terminal UP the d-c output voltage on terminals 5 and 7 of V2 will be negative. The magnitude of d-c voltage appearing at the output of the phase-sensitive detector increases with increasing target angle until the limiting value of the phase-sensitive detector output voltage is reached. This limiting value of output voltage is determined by the



voltage of the 1-kc switching oscillator. The horizontal phase-sensitive detector V3 functions in the same way as the vertical phase-sensitive detector except that its output voltage is determined by the relative levels of signal on the terminals RT and LFT in Figure 5.

## 21.6 ENABLING RECEIVER

The enabling receiver shown in Figure 9 is similar in its principle of operation to the one used in the Harvard NO181F. It, however, uses an amplifier which is entirely independent of the steering receiver amplifier; there is no sensitivity control and the amplitude gate is not included in it. The signal for the en-

abling receiver is taken from terminal 1 of the input circuit shown in Figure 5 of Chapter 19 which will cause a signal to be first observed in the plate circuit of the discriminator driver. The discriminator driver also serves as the limiter stage in the system. The resulting gain is such that in normal operation there is about a 6-db difference between the signal level on terminal 1 which produces a just perceptible signal in the plate circuit of

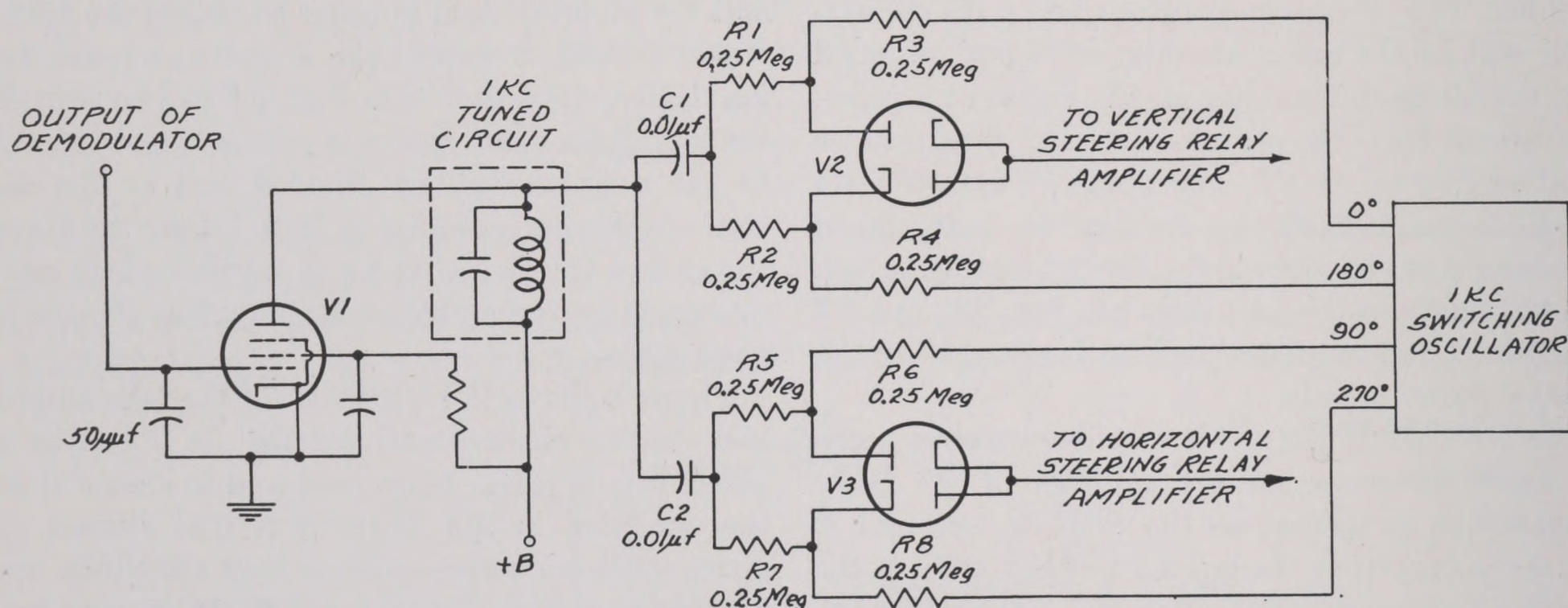


FIGURE 8. 1-kc amplifier and phase-sensitive detectors. (Note: Pin numbers of V2 and V3 are 1, 2, 5, and 7, starting with the lower left-hand cathode and going clockwise.)

abling amplifier is taken from terminal 1 of the input circuit indicated in Figure 5 of Chapter 19. The first stage of amplification operates at the normal signal frequency of 60 kc. This stage uses an inductive load in the plate circuit of the tube. The output of this stage is coupled to the grid of the converter stage through a 0.0001- $\mu$ f condenser. This arrangement allows for a voltage gain from the input of the 60-kc amplifier to the grid of the converter stage of about 30 db at 60 kc, while at 7 kc, which is the frequency to which the signal is converted, the gain from the input of the 60-kc amplifier to the grid of the converter is about -8 db. All of the tubes used in the amplifier and converter stages are 6AK5 miniature pentodes. The 7-kc band-pass filter which serves as the plate load for the converter has been redesigned so that the conversion gain is considerably increased from that available in the Harvard NO181 system.

Following the converter is a two-stage amplifier. The first stage of the amplifier is resistance-coupled

the discriminator driver and the signal level which produces complete limiting in the discriminator driver. This entire amplifier, from the input circuit to the discriminator driver, has one stage less of amplification than was used in the original HUSL NO181 enabling system. At the same time it can be operated so that a signal of -125 dbv on the transducer will produce complete limiting of the discriminator driver. In the Harvard NO181F system, limiting of the discriminator driver took place at a signal level on the transducer of -105 dbv. It would be possible to operate this amplifier so that limiting takes place at a signal level of -136 dbv, if it could be used in a torpedo of sufficiently low noise level.

The discriminator terminals 1 and 2 of Figure 9 are connected to the two diodes V1 and V2. By means of these two diodes and the diode V3, the output at the terminal P will be positive regardless of the polarity of the signal out of the discriminator, and therefore, regardless of whether the echo signal has



a higher or a lower frequency than the reverberation signal. The potential generated at *P* is amplified by means of the pulse amplifier which is incorporated in the steering receiver and shown in Figures 5 and 7. The condensers C5, C6, C7, and C8 and the resistors R5, R6, and R7 of Figure 9 form a filter in one side of the discriminator circuit, while the condensers C9, C10, C11, and C12 and resistors R8, R9, R10 form a filter in the other side of the discriminator circuit. These filters are identical with the filter

plays the role of varying the effective value of the condenser C14 in the tank circuit of the oscillator by means of the potential applied to the grid 4 of V4. The relay is operated by means of a cam-operated switch in the time base, which is so arranged that this relay is closed for about 50 msec immediately following transmission. However, in order to prevent sampling of the discriminator output, during receipt of an echo when the torpedo is near enough to a target so that an echo is received during this 50-msec

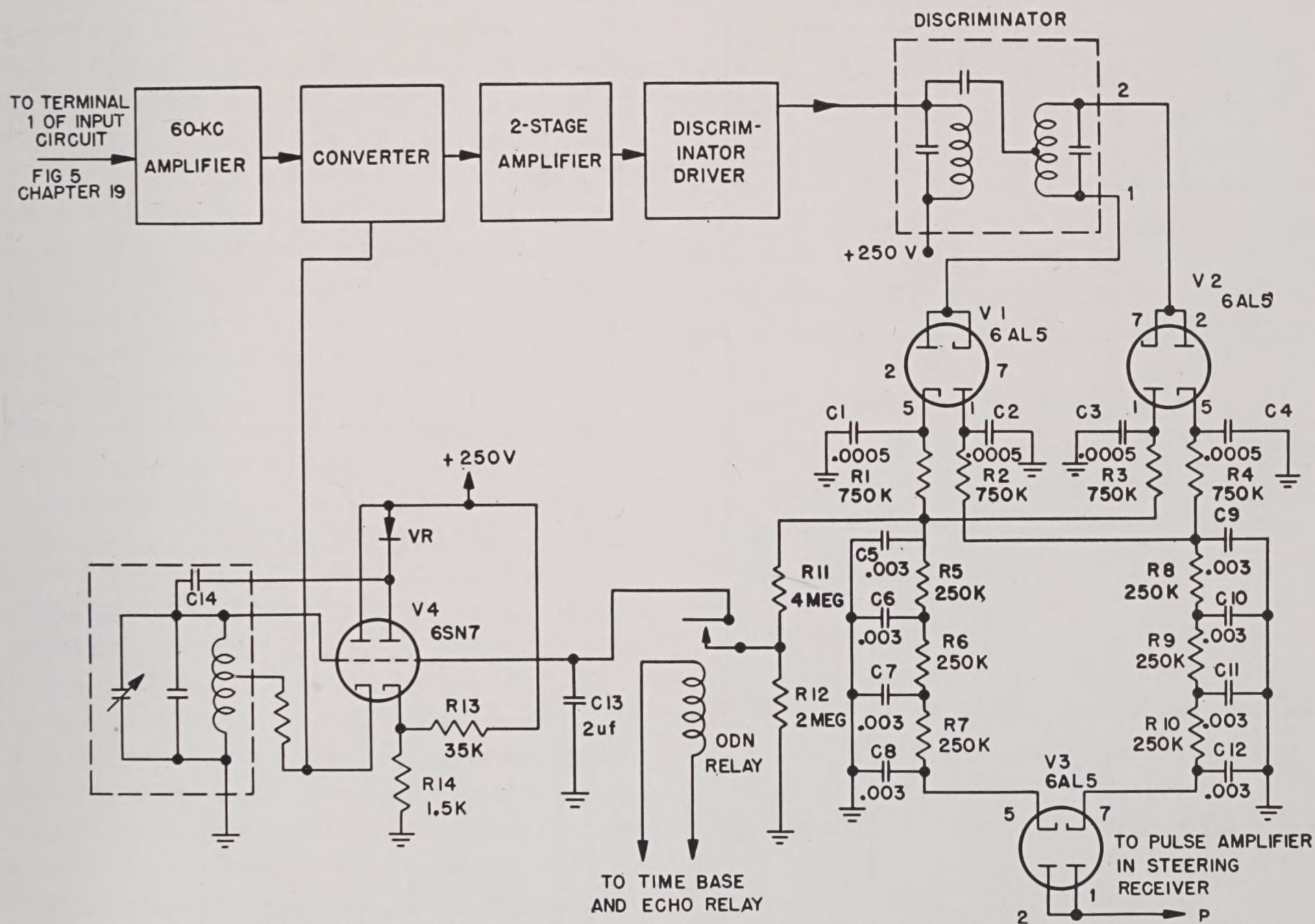


FIGURE 9. Doppler-enabling circuit. (Pin numbers of 6SN7 are 3, 1, 2, 5, 4, and 6, clockwise from lower left-hand cathode.)

which was used in the discriminator circuit in the Harvard NO181F system. The relay indicated serves to connect the output of one side of the discriminator to the grid 4 of V4, during an interval of 50 msec following transmission.

The 1-2-3 section of V4 is the local 53-kc oscillator which supplies signal to the screen of the converter stage. The automatic frequency control, which adjusts the oscillator frequency so that the output of the converter will be at the frequency of the discriminator center when reverberation is the source of signal, is accomplished by means of the 4-5-6 section of V4 with the varistor VR. This arrangement

period, one side of the relay coil is connected to its source of potential through a contact on the echo relay which will be described in the next section. By arranging the switch, operated by the time base so that it simply connects the other side of the relay coil to ground, the arrangement insures that the relay will be closed during the entire 50-msec period providing no echo is received, but immediately on receipt of an echo signal the circuit between the one side of the relay coil and the 48-v power supply will be broken and the ODN relay will drop open.

Since this circuit is entirely independent of other parts of the electronic system, except for the furnish-



ing of the enabling signal to the pulse amplifier in the steering chassis, it is possible to completely remove this enabling receiver from the other gear and have the rest of the device operate without doppler enabling providing a readjustment is made on the

## 21.7 RELAY CONTROL CIRCUIT

The details of the relay control circuit incorporated in the control panel are shown schematically in Figure 10. The following four relays are used.

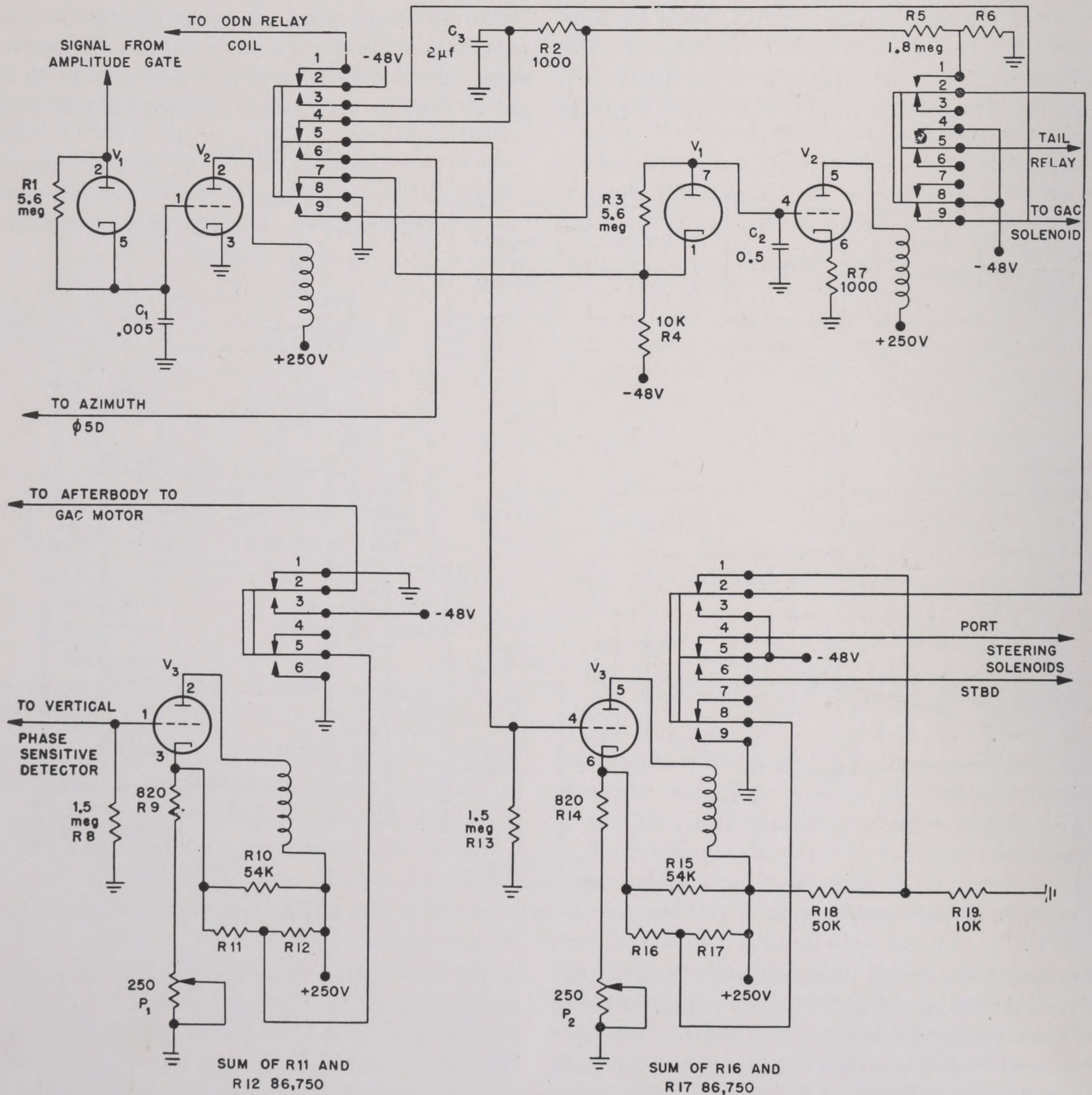


FIGURE 10. Control circuits.

value of the bias on the demodulator. This is provided for by the switch shown in Figure 7, which makes it possible to use the steering receiver as an echo-ranging receiver without doppler control or as a noise-steering receiver in addition to its normal method of operation.

1. An echo relay which is actuated during the time of receipt of an echo.
2. An enabling relay which is actuated by the echo relay, but which remains closed for a period of about 6 sec following the last echo of a sequence.
3. An azimuth steering relay which is positioned



by the information supplied by the azimuth phase-sensitive detector.

4. The vertical steering relay which is positioned by the information last received from the vertical phase-sensitive detector.

The following is a description of the operation and functions of the four relays:

#### 21.7.1 Echo Relay

The echo-relay amplifier is operated by the signal which appears on the grid of the demodulator shown in Figure 5 which is normally maintained at  $-22$  v relative to ground. This potential serves as the necessary bias for the grid of the echo-relay amplifier. The 2-5 section of the diode V1 shown in the Figure 10 is placed in series with the grid of the echo-relay amplifier to provide, with the resistor R1, a fast-charge slow-discharge circuit for the condenser C1. R1 and C1 provide a small holding-time constant to delay somewhat the opening of the echo relay following receipt of an echo. This delay is necessary because of the fact that this relay operates the glide-angle control solenoid in the afterbody and when vertical steering takes place, it is necessary to hold the glide-angle control solenoid actuated for sufficient time to allow the glide-angle control motor to complete a portion of its operation. The details of this will be described in the next section covering the functions of the afterbody circuits.

The glide-angle control solenoid is operated by the 2-3 contacts of the echo relay and provision for the removal of the ODN frequency correction, when an echo is received during the 50-msec ODN sampling period, is provided by the No. 1 contact. This is accomplished by the fact that the ODN relay coil, shown in Figure 9, is connected to the  $-48$ -v supply via contacts 1-2 of the echo relay when this relay is open. Receipt of an echo immediately breaks this contact permitting the ODN relay to drop open.

The 5-6 contacts, on the echo relay serve to connect the azimuth phase-sensitive detector to the grid of the azimuth steering-relay amplifier during the time an echo is being received. When the echo relay is open, the 5-4 contacts connect this steering amplifier grid to the azimuth automatic rudder-reversal circuit which will be described later. Opening the 7-8 contacts allows a 48-v surge to flow via R4 and the 1-7 section of the diode V1 to charge the condenser C2 and cause the enabling relay to open. The discharge of C2 through R3 and the 7-8 contacts of the

echo relay provide the holding time required for the enabling relay. The components indicated in the figure provide a holding time of about 5.7 sec.

#### 21.7.2 Enabling Relay

The normal condition of the enabling relay is closed. Closing of the echo relay results in grid terminal 4 of V2 being driven negative, which causes the enabling relay to open. The relay is held open for about 5.7 sec in the absence of further echoes because of the time constant of C2 and R3. The 1-2 contacts on this relay are involved in the azimuth automatic rudder-reversal feature to be described later. The contacts 4-5 connect  $-48$  v to the coil of a relay in the afterbody which sets up the circuits in the afterbody for acoustic control. The contacts 8-9 connect  $-48$  v to the glide-angle control solenoid, when this relay is in the normal closed condition, in order to permit the glide-angle control to be returned to the neutral position after an attack has been broken off.

#### 21.7.3 Vertical Steering Relay

The 1-2-3 section of V3 is the vertical steering-relay amplifier. It receives its signal directly from the vertical phase-sensitive detector. Contacts 1, 2, and 3 permit connecting one terminal of the glide-angle control motor to either  $-48$  v or ground. Since the other terminal of the motor is connected to  $-24$  v, the position of this relay determines the direction of rotation of the glide-angle control motor. Operation of the glide-angle control motor is determined by the echo relay, the enabling relay, and a range-measuring cam in the time base. The details of these circuit arrangements will be described in the next section. The 5-6 contacts on the vertical steering relay provide a holding feature by grounding the junction of R11 and R12 when the relay is closed. By means of this holding feature the relay can be made to open on a  $-2$ -v signal on the grid of the amplifier and close with a  $+2$ -v signal on the grid and it will retain its last position until a suitable signal arrives to change it.

#### 21.7.4 Azimuth Steering Relay

The azimuth steering-relay amplifier is connected to the azimuth phase-sensitive detector by way of the 5-6 contacts of the echo relay. This relay amplifier has the same sensitivity and holding feature as is incorporated in the vertical steering relay with the 8-9 contacts on the relay used to control the holding



feature. The automatic rudder reversal feature of the azimuth steering system is arranged through the contacts 1, 2, and 3. The 4, 5, and 6 contacts are the steering contacts which provide for  $-48$  v to be connected to one or the other of the azimuth steering solenoids. The ground return for these solenoids is provided through the relay in the afterbody which is operated by the enabling relay. Before the first echo is received, it is impossible for the solenoids to be operated by the azimuth relay. When an echo is received, the closing of the enabling relay provides for connection of the ground return from the solenoid so that the azimuth steering relay takes over control of the azimuth steering from the gyro. The gyro lock-off feature in the afterbody provides for permanent ground return of the solenoids after a series of about ten echoes has been received. When this has been accomplished the azimuth steering relay will retain control of the azimuth steering regardless of whether echoes are being received or not.

#### 21.7.5 Azimuth Automatic Rudder-Reversal Feature

Assume that the torpedo is steering to starboard, the azimuth rudder relay is down, and the torpedo is in an attack. Under these conditions  $-48$  v are connected through the 3-2 contacts of the azimuth steering relay and the 2-1 contacts of the enabling relay, and R5 and R2 to the terminal of the condenser C3. While the echo relay is open, C3 is connected through the 4-5 contacts of the echo relay to the grid of the azimuth steering relay. When the condenser C3 arrives at a sufficiently negative potential ( $-2$  v) the azimuth steering relay will be thrown open, causing the torpedo to steer to port. The same sequence would be carried out if the azimuth relay had originally been open except that, in this case, terminal 2 of the azimuth relay would be connected to the bleeder circuit R18 and R19 which supplies a positive potential with which to charge C3, which would cause the relay to close when C3 arrives at a potential of  $+2$  v. The action of the 8-9 contacts on the echo relay is to discharge C3 through R2 each time an echo is received so that the rudder reversal can take place only when an attack breaks off. Since C3 is charged through the 2-1 contacts of the enabling relay the rudder reversal must take place during the holding time of this relay. Since only one reversal is desired when an attack breaks off, the time constant of the rudder-reversal circuit which is de-

termined by C3, R5, and R6 must be more than half the holding time of the enabling relay, and to insure the reversal taking place, the time constant must be less than the holding time of the enabling relay.

#### 21.7.6 Sequence of Events in an Attack when an Echo is Received

The echo relay drops closed and remains closed for several milliseconds after the end of the echo. The azimuth and vertical steering relays take up settings which are determined by the outputs of the azimuth and vertical phase-sensitive detectors. The vertical steering relay will not be able to exert control on the glide-angle control system unless the range is less than 250 yd, since the actuation of the glide-angle control solenoid by the echo relay is accomplished by way of a cam-operated range switch in the time base. The azimuth relay will immediately take control of the azimuth steering from the gyro and the gyro lock-off motor will start. Three separate possible cases will be considered. The first possibility is that only one or two echoes are received and the range is greater than 250 yd. Under this condition, no vertical steering takes place. After the last echo, the azimuth rudder relay will hold for about 4.5 sec, when the rudder will reverse, causing the torpedo to start to recross the beam. However, at the end of about 6 sec following the last echo, the enabling relay will drop closed and return the torpedo to gyro control. The second possibility is that a series of ten or more echoes are received so that the gyro lock-off motor has completed its cycle. The action will be the same as before, except that after rudder reversal the torpedo will continue to circle in the direction determined by the reversed-rudder relay position. The third possibility is that a series of echoes have been received for a sufficient time to cause the gyro lock-off to complete its cycle and the attack has carried the torpedo into the range where vertical steering can take place. The glide-angle control functions to allow the torpedo to correct its course by about 1.5 degrees in the vertical plane each time an echo is received within the 250-yd vertical steering range. If the torpedo loses contact with the target, it will continue to climb at the climb angle determined by the last setting of the glide-angle control until the enabling relay drops closed; i.e., until about 6 sec after receipt of the last echo. After this, the glide-angle control will be returned to its initial neutral position by one increment of angle in each ping interval. In the mean-



time, the azimuth rudder reversed after a lapse of 4.5 sec from the last-received echo. Since the glide-angle control return takes place in increments, the torpedo will have a chance to reverse its course and sweep across the beam before it has a chance to return to its hydrostatic running depth. If the loss of contact occurs at a point very close in, there is a chance that the automatic rudder-reversal feature will cause the torpedo to strike the target in spite of loss of acoustic contact.

## 21.8 CIRCUITS IN THE TORPEDO AFTERBODY

Figure 11 shows the circuit arrangements for the afterbody of the torpedo. The circuits are arranged for the use of generator power supplies located in the afterbody. The time base is operated as a system of cams driven by the main motor shaft and is indicated in the figure as the cams C1 through C4. The azi-

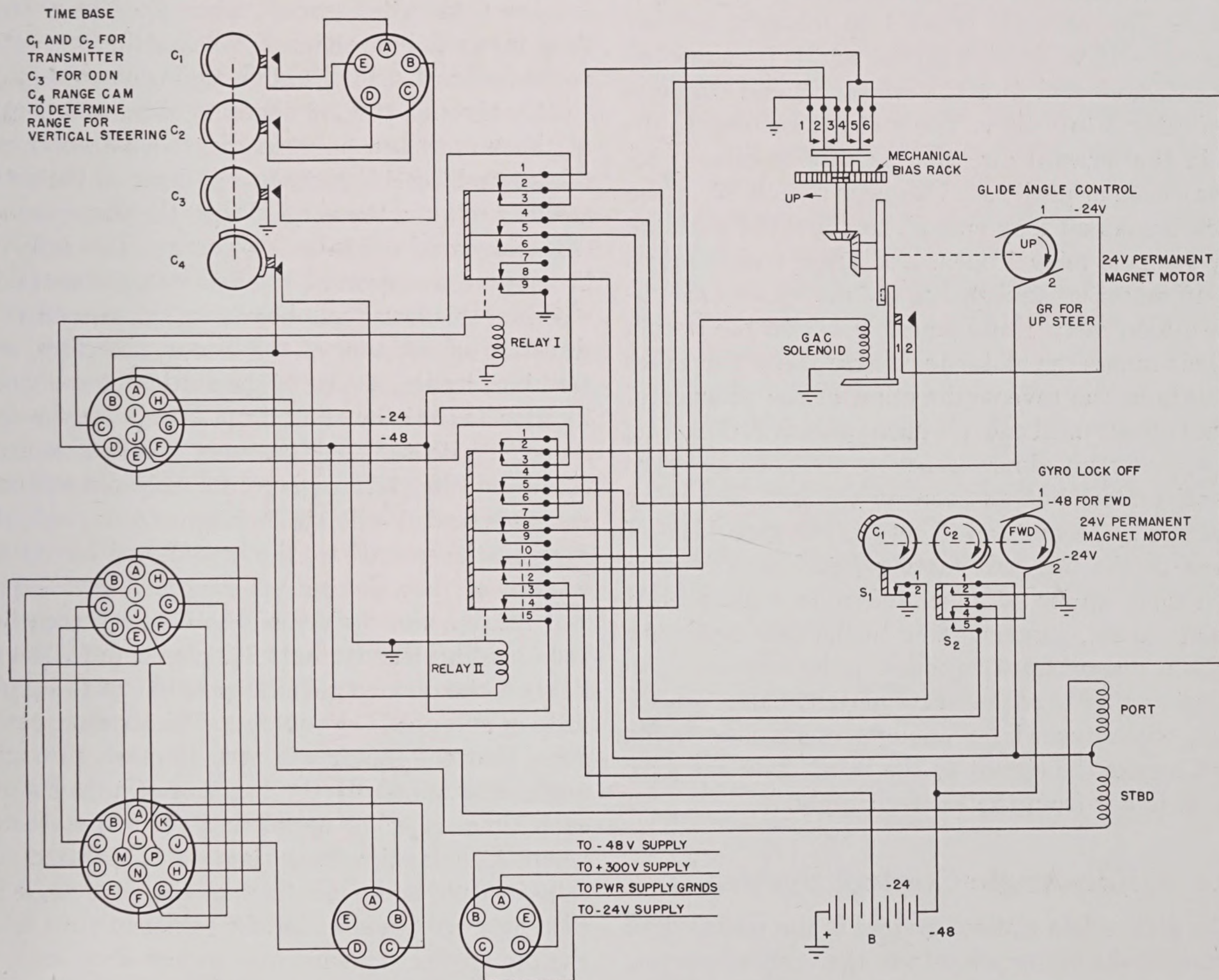


FIGURE 11. Afterbody circuits.

The time constants given for the automatic rudder reversal, the holding of the enabling relay, and the gyro lock-off are not necessarily the values which will eventually be used, since their value will have to be determined by the body dynamics of the torpedo. In order to prevent broaching of the torpedo when it loses contact close in, it will probably be necessary to have a ceiling switch in the afterbody which will permit immediate return to hydrostatic control if acoustic contact is lost at depths less than 10 ft.

muth steering solenoids are arranged so that they take over control of the steering from the gyro when they are actuated by the relay circuits. The relay designated as relay 2 in Figure 11 is closed by the 48-v power supply when the power supplies are turned on. This is provided in order to permit recycling of the glide-angle control system and the gyro lock-off system after prerun tests have been completed. The following is a description of the various components and their functions.

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### 21.8.1 Provision for the Gyro Lock-off

The gyro lock-off consists of a small 24-v permanent-magnet motor which drives cams C1 and C2 through a reduction gear. In the figure, the arrows on the motor and cams indicate the direction of rotation of the system when it is progressing toward the gyro lock-off condition. At the start, cam C1 is in such a position that it holds the switch S1 open. When the first echo arrives, closing of the enabling relay on the main chassis actuates relay 1 causing it to close. This connects brush 1 on the gyro lock-off motor to  $-48$  v. Brush 2 on the motor is connected via contacts 3 and 4 of the switch S2 and contacts 5-6 of relay 2 to  $-24$  v. The motor continues to rotate in the forward direction as long as relay 1 remains closed or until cam C2 opens switch S2. If the attack breaks off long enough to allow the enabling relay to open, relay 1 opens and brush 1 of the gyro lock-off motor is connected to ground by way of contacts 4-5 on relay 1 and contacts 1-2 on the switch S1. This causes the motor to reverse and it continues to rotate in the reverse direction in the absence of further echoes until cam C1 opens switch S1 breaking the motor circuit. Spurious echoes will start the gyro lock-off motor, but as soon as the enabling relay drops open, the motor will return the gyro lock-off system to the original starting position. The time which is set up for gyro lock-off to be accomplished is about 15 sec, corresponding to the time necessary for about ten consecutive echoes to be received. The lock-off feature is achieved by means of the cam C2 which, when turned far enough, opens switch S2, which breaks the circuit to the brush 2 on the gyro lock-off motor from the  $-24$ -v supply.

### 21.8.2 Glide-Angle Control System

The glide-angle control system is the means used to transfer the information from the vertical steering relay to the elevators. This is done by adding increments of mechanical bias to the pendulum in the immersion mechanism. The bias is added to the pendulum in such a way that it is compensated for by a tilt of the torpedo body through a definite number of degrees. The amount of bias added to the pendulum on each received echo is about 1.5 degrees.

It is desired that vertical steering be restricted to a target range of about 250 yd or less. This is accomplished by the use of cam 4 in the time base which keeps its switch closed during the time that an echo could be received from a target range of 250 yd or

less. If an echo is received within this range, the echo relay in the panel will be closed which connects  $-48$  v, via terminal *D* on the large *AN* plug, terminal *E* on the small *AN* plug, the switch operated by cam 4 and the 11-12 contacts on relay 2 to the glide-angle control solenoid. This solenoid is the coil of a relay which, when it is actuated, closes contacts 1-2, while the extended arm on the relay is pulled away from the disk *D*. This arm has a pin which fits into holes around the edge of the disk *D* so that the contacts 1-2 are held closed, except when the pin is free to drop into a hole in the disk. Closing the contacts 1-2 connects brush 1 of the glide-angle control motor to  $-24$  v through the 2-3 contacts of relay 2. Brush 2 of the motor is connected via the 2-3 contacts of relay 1 and the *AN* plugs to a swinger on the vertical steering relay in the panel. When the phase-sensitive detector signal indicates up-steering, this brush will be connected to ground, whereas if it indicates down-steering, this brush will be connected to  $-48$  v. The direction of rotation of the motor, therefore, is determined by the setting of the vertical steering relay. As soon as the echo relay drops open after the end of an echo, with the enabling relay still in its actuated condition, the glide-angle control solenoid will be unactuated and it will try to return to normal. However, in the meantime, the disk *D* will have turned enough so that the pin on the extended relay-arm will ride on the surface of the disk between holes, thus holding the contacts 1-2 closed until the next hole on the disk comes into position so the pin can drop in and open the contacts. This arrangement insures that the motor will turn the disk through an angle determined by the location of adjacent holes each time an echo, permitting vertical steering, is received. A small holding time is incorporated in the echo relay to make certain that the glide-angle solenoid may remain actuated for sufficient time so that the pin on the extended arm cannot drop back into the same hole from which it is pulled out.

If an attack is broken off, the enabling relay will eventually drop open. When this occurs, the relay setup on the steering panel will be such that the glide-angle control solenoid will be actuated during each interval that the switch operated by cam 4 in the time base is closed. If some bias has been introduced on the pendulum by means of the glide-angle control system, contact 2 in the switch which is operated by the mechanical bias rack will be closed either against contact 1 or 3 depending on whether the bias introduced is for up or down steering. When



the enabling relay in the steering panel is unactuated, relay 1 in Figure 11 will open and brush 2 on the glide-angle control motor will be connected via contacts 2-1 on relay 1 to contact 2 of the switch operated by the mechanical bias rack. The polarity of contacts 1 and 3 is such that the motor will be driven in a direction so that the mechanical bias rack will be returned to its neutral position. Because of the intermittent operation of the glide-angle control solenoid under this condition, the glide-angle control bias will be returned by one of the increments of bias during each ping interval. When the bias rack has been returned to the neutral position, contact 2 on the bias-rack switch will be in a free position between contacts 1 and 3, thus breaking the motor circuit. In order to prevent broaching of the torpedo when acoustic contact is lost near the end of an attack, a pressure-operated ceiling switch is placed in parallel with the switch operated by cam 4. This permits the glide-angle control motor to return the pendulum bias to the neutral condition immediately on opening of the enabling relay if the torpedo is at a depth shallower than the setting of the ceiling switch.

The provision for recycling of the gyro lock-off and the glide-angle control is made by means of the battery *B* and the change of connections provided when relay 2 is unactuated by turning off the source of 48-v power. If the gyro lock-off has completed its cycle so that S2 is open, brush 2 of the gyro lock-off motor will be connected to the 24-v terminal on the

battery *B* by way of contacts 4-5 or relay 1 and contacts 1-2 of switch 1. This will permit the motor to start to recycle even though the gyro lock-off motor has turned sufficiently to allow the switch S2 to open. Brush 2 of the motor will be connected to the -24-v terminal of the battery *B* by way of contacts 4-3 of the switch S2 and contacts 4-5 of relay 2 so the motor will continue to recycle until cam 1 opens the switch S1 which is the condition for starting of the system.

The glide-angle control solenoid is connected to the -48-v terminal of the battery by way of contacts 10-11 of the relay 2 and the 4-5-6 contacts operated by the mechanical bias rack providing the glide-angle control is not in the neutral position. This will cause the 1-2 contacts operated by the glide-angle control solenoid to be closed and to remain closed until the mechanical bias rack is returned to the neutral position. Brush 2 of the glide-angle control motor will be connected to either ground or the -48-v terminal *B* by the mechanical bias-rack switch, if it is not in the neutral position and the polarity determined by contacts 1, 2, and 3 are such that the rack will be run back toward the neutral position. As soon as the neutral position is reached, the motor circuit will be broken by the 1-2-3 contacts in the mechanical bias-rack switch stopping the motor. At the same time the connection to the glide-angle control solenoid will be broken by the 4-5-6 contacts on this switch. <sup>a</sup>

<sup>a</sup> See references 6, 11-13, 15, 16, 18-20, 26, 27, 29-32, 37-47 for additional material on topics in this chapter.



## Chapter 22

# BELL TELEPHONE LABORATORIES 157B AND 157C SYSTEMS

22.1

### INTRODUCTION

THE original Bell Telephone Laboratories [BTL] development was an echo-ranging system to be used in the submarine-launched Mark 14 torpedo and was known as Project 157B. However, when the use of the Mark 18 electric torpedo began to supersede the use of the Mark 14, BTL was asked to modify their system for use in the Mark 18 torpedo. The

ing transmission, so that equal acoustic signals, in phase with each other, are transmitted into the water. The receiver consists of two similar amplifiers, with each amplifier connected to the output of one-half of the transducer. At the output of each amplifier channel is a threshold stage which imposes the requirement that a signal level developed in the transducer must exceed some predetermined value as a function of time after transmission in order to

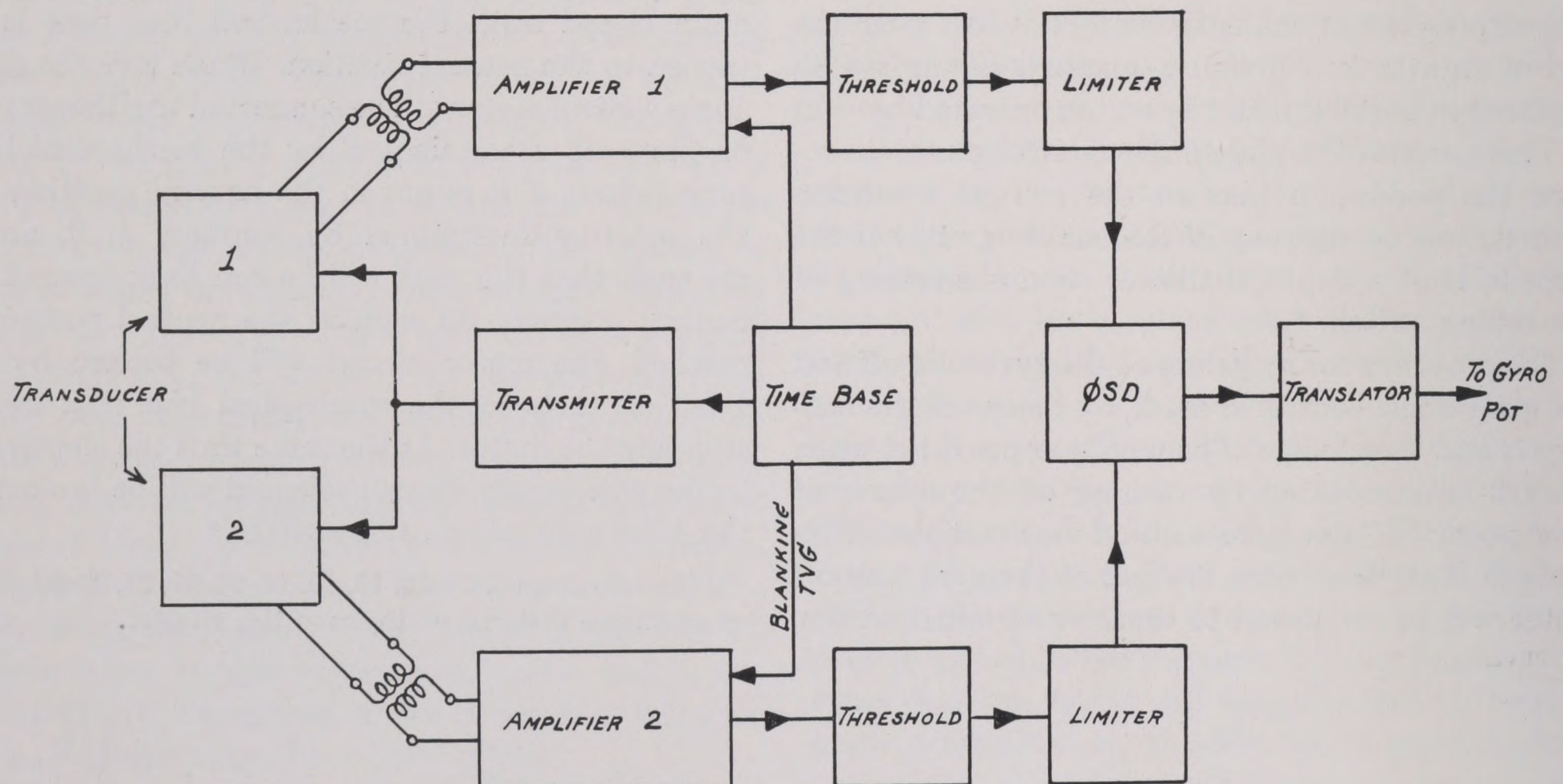


FIGURE 1. Block diagram of 157C system.

work on the adaptation of the system to the Mark 18 was being concluded at the end of World War II, and while no tests had been run on this modified device, some units, designated as 157C, were about ready for field operations. Since the only essential differences between the 157B and 157C systems are those necessary to adapt the systems to the two different torpedoes, the description in this report will be confined to the one used in the Mark 18 torpedo, the 157C.

A block diagram of the system is shown in Figure 1. Acoustic control is confined to the azimuth plane with the normal hydrostatic control in depth. The transducer is divided into two halves in the azimuth plane with the two halves connected in parallel dur-

pass this threshold stage. The time variation in signal level which is imposed is controlled by a *time-varied gain* [TVG] control on the receiving amplifiers. Following threshold stages are limiter stages. The characteristics of the threshold and limiter stages are such that about 2 db of signal level above that necessary to pass the threshold stage is sufficient to limit the limiter stage. This assures that a signal level, a very little higher than the minimum permitted to pass the threshold stage, will result in a level out of the limiter stage which is independent of received signal level. The outputs of the two limiter stages are fed to a phase-sensitive detector. The phase-sensitive detector measures the electrical phase relation between the signals which have been supplied by the



two halves of the transducer, and from this electrical phase difference the target bearing relative to the axis of the torpedo is determined. The information determined by the phase-sensitive detector is supplied to a device known as a translator. The translator is a mechanical system which is connected to the cam plates on the torpedo gyro. The correction to be applied to the course of the torpedo, as determined by the phase-sensitive detector, is applied directly to the gyro cam plate by the translator. In this way, the torpedo remains under gyro control for the entire course of the run; but, after an attack begins, the system is able to make a correction on the setting of the gyro course of the torpedo on each received echo.

It is necessary to make provision in the phase-sensitive detector system against the torpedo homing on the wake. This is done by means of a preferred-side steering. At the time the torpedo is fired, the side of the target on which it is being fired is determined and a switch operable from the outside of the torpedo body is set so that, if the torpedo is fired toward the port side of a target, the system will prefer echoes reflected from the point on the target furthest to port. This means that when an echo is received from an extended target including the full length of a ship and its wake, the torpedo will home on the bow end of the entire system.

The transmitter supplies about 1,500 watts of electric power to the transducer. The transmitted pulses are 3 msec in length and they are spaced at 1-sec intervals. This spacing of the transmitter pulses makes the maximum acoustic range of the torpedo about 800 yd. The frequency at which the system operates is about 28 kc.

## 22.2

## TRANSDUCER

Figure 2 shows the details of the elements of the transducer used. It consists of an array of piezoelectric crystals mounted on a steel resonator plate which is enclosed in a chamber formed by the resonator plate and a thin steel dome. The crystals are ammonium dihydrogen phosphate 45-degree z cut. Twenty-four crystals are used with eight of them half-amplitude in order to obtain a system which suppresses minor lobes. The crystals are separated from the steel plate by means of ceramic insulators. The crystals are cemented to the ceramic insulators and the ceramic insulators are in turn cemented to the resonator plate. The space between the resonator

plate and the thin steel dome is filled with Union Carbide and Carbon Corporation's UCON HB 600 fluid.

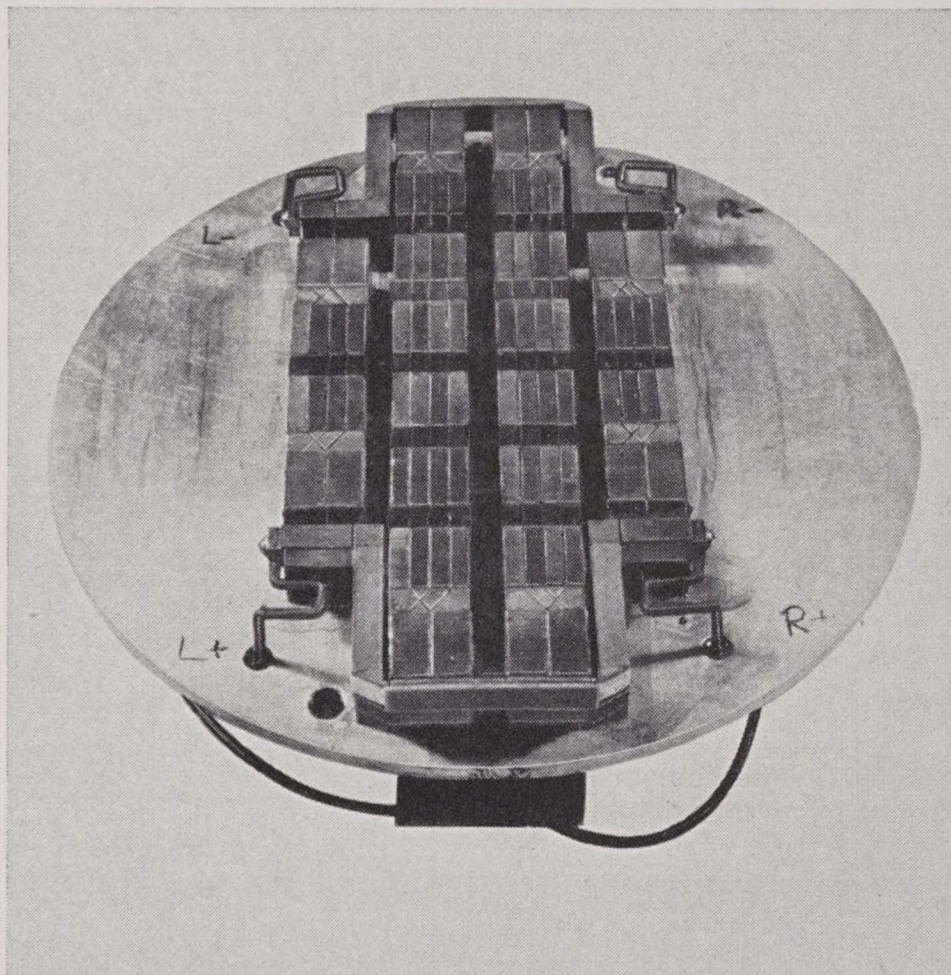


FIGURE 2. Transducer crystal array.

The steel dome is 0.030 in. thick and mechanical reinforcement is provided by an internal grill work of 3/16-in. stainless steel rods. Figure 3 shows details of the dome. Figure 4 shows the directivity patterns

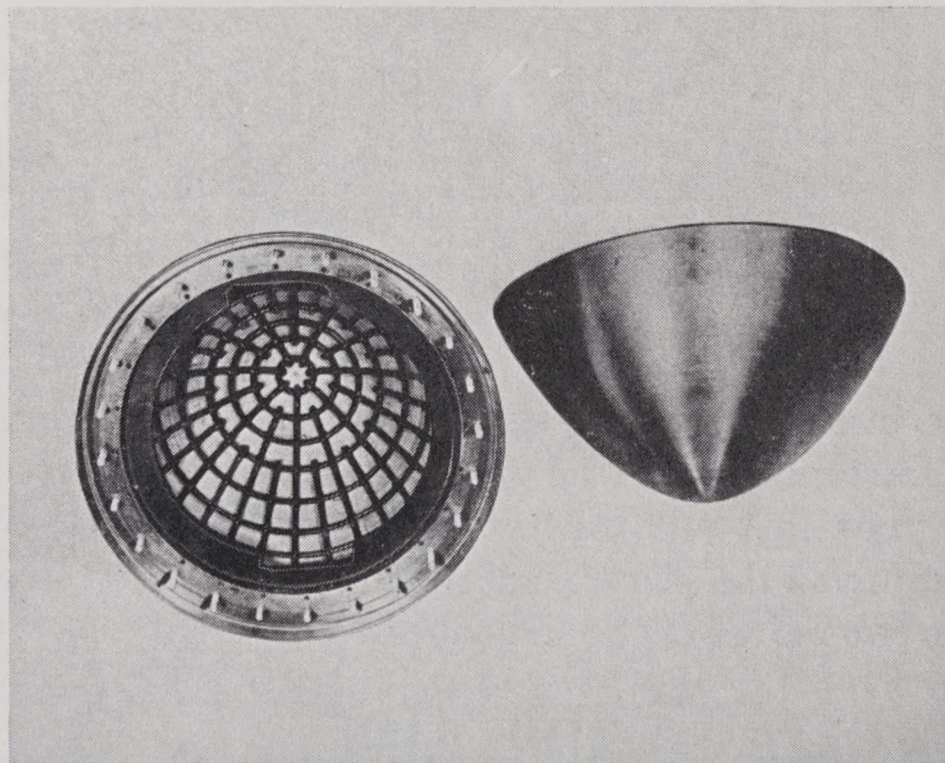


FIGURE 3. Transducer dome.

for this transducer in both the horizontal and azimuth planes and for both transmission and reception. Figure 5 shows the electrical phase angle between the signals generated in the two halves of the transducer measured as a function of the angle of



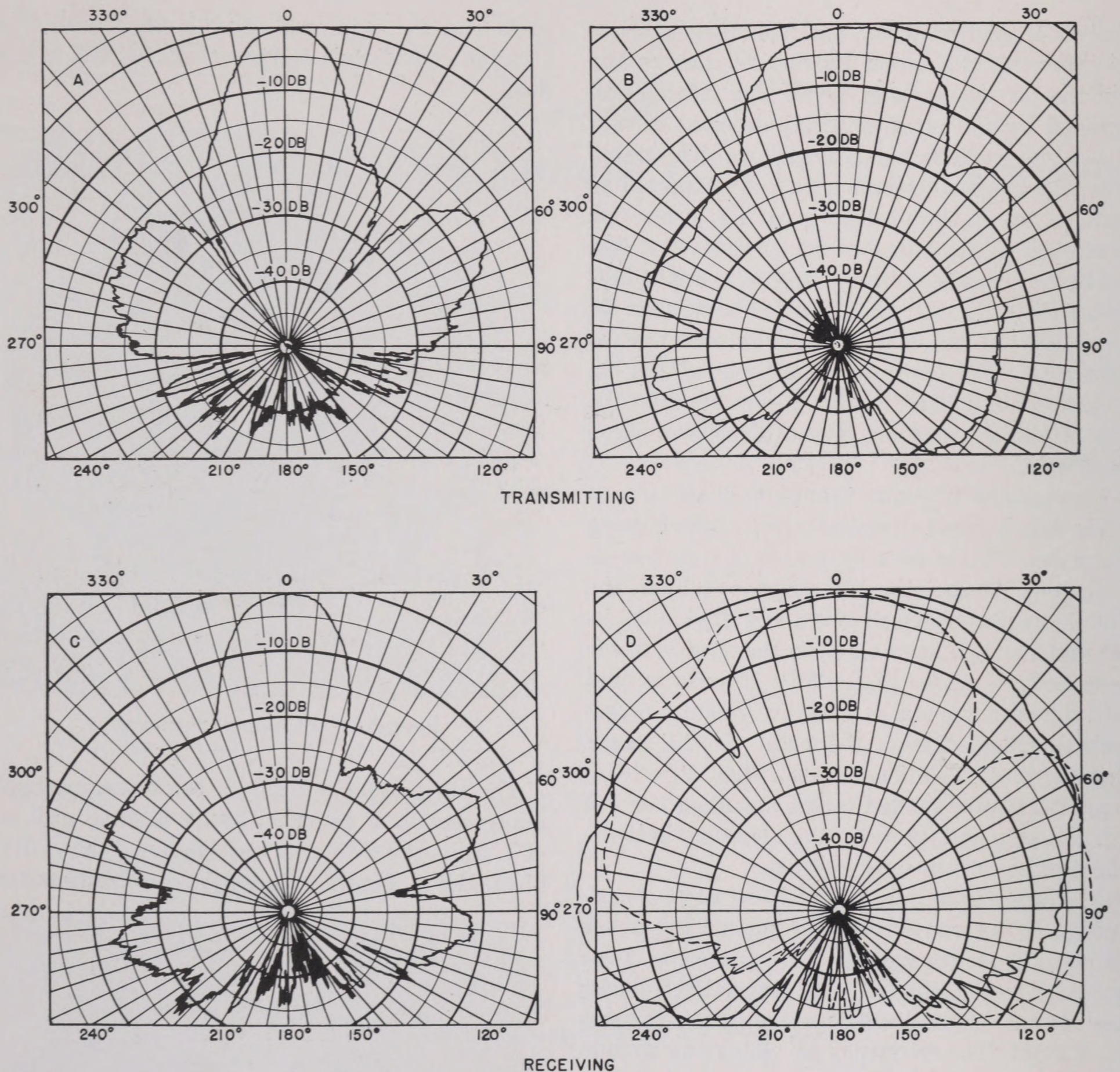


FIGURE 4. Directivity patterns of transducer.

the incident acoustic signal. This is an important characteristic since the system measures the bearing of the target relative to the axis of the torpedo by comparing the phase angle of the signal generated in the two halves of the transducer.

### 22.3 TIME BASE

The operation of the torpedo is based on the use of 3-msec pulses transmitted at 1-sec intervals, making the maximum possible acoustic range of the torpedo a little over 800 yd. During transmission, transients are induced in the tuned circuits of the receiver which persist for a short time following transmission. In order to prevent false steering on these transients

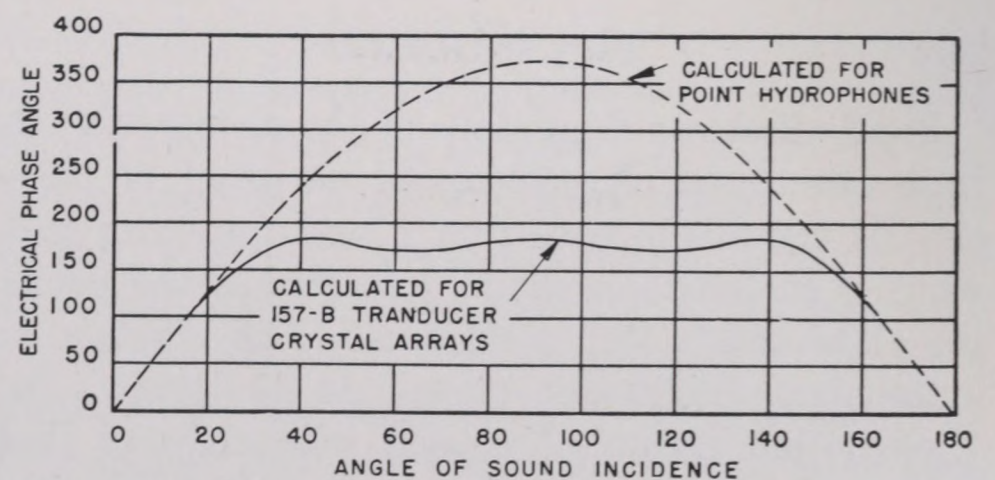


FIGURE 5. Electrical phase angle plotted as a function of target angle for the hydrophones.

the receiver is blanked for a total of 40 msec beginning at the time of start of transmission. Figure 6 indicates diagrammatically the sequence of operations

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controlled by the time base. The time base consists of a multivibrator which actuates relays during its on period. A schematic of the entire time-base system is shown in Figure 7. The normal off period of the

by which the end of C1 connected to terminal 3 of V2 is rapidly charged to approximately +300 v during the 50-msec on period. Since this condenser has a large capacity (1  $\mu$ f), a low-impedance charging

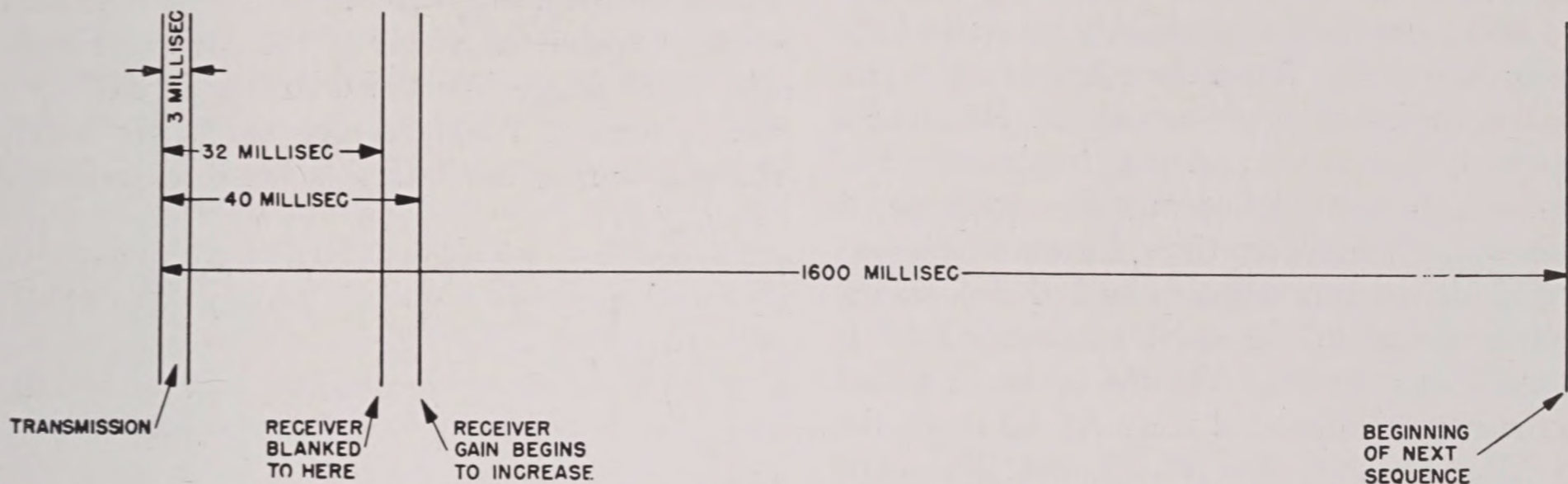


FIGURE 6. Sequence of events in the time base. Note: Dimension "1600 millisecc" should read 1000 millisecc.

multivibrator is 950 msec and its on period is approximately 50 msec. Timing of the off period is determined by C1, R1, and P1. Adjustment of the off period is accomplished by means of the poten-

path is required to provide full charging of this condenser. This charging path is provided by the 1-2-3 section of the tube V2 acting as a cathode follower.

The normal operation of the panel requires that

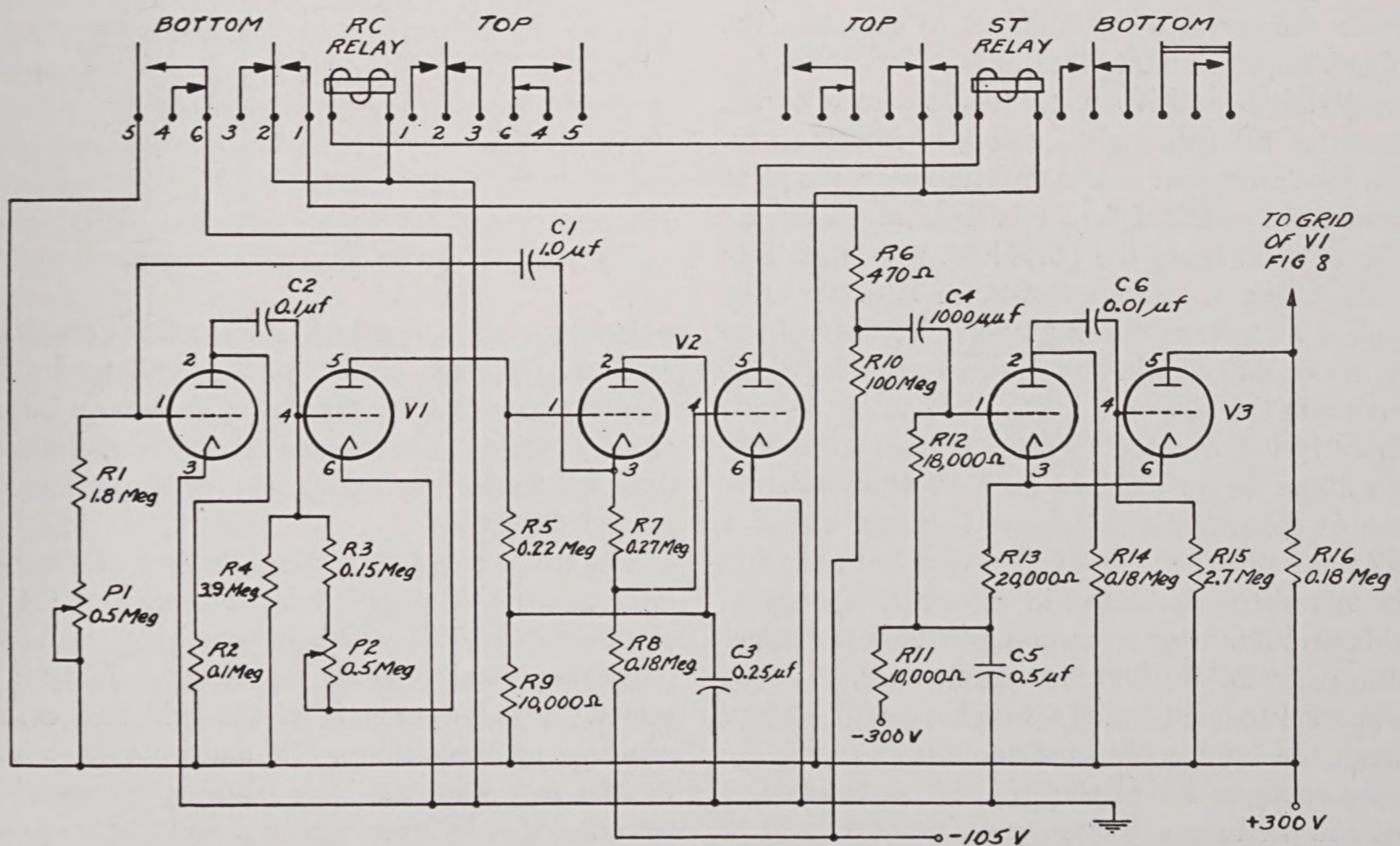


FIGURE 7. Time-base circuit.

tiometer P1. The on period is controlled by C2, R3, and P2, when the latter two are connected to the +300-v supply by the 5-6 contact of the relay RC. An unusual feature of the multivibrator is the circuit

the reverberation control relay RC shall be closed for 40 msec. The multivibrator circuit is designed to insure stability of this requirement. The operation is as follows: When the 2-3 section of the tube V1 be-

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gins conducting, terminal 4 is driven negative and current from terminal 5 to 6 ceases. The resultant flow of current from terminal 5 to 6 of V2 actuates the starting relay *ST* which in turn actuates the relay *RC*. During this period, the voltage on terminal 4 of V1 has risen only slightly because of the high resistance of R4. When the contacts on the reverberation control relay *RC* are closed, R3 and P2 are returned to +300 v and the time constant of these resistors in combination with the condenser C2 determines the remaining time during which terminal 4 of V1 remains negative and, therefore, the time until current in the starting relay coil *ST* is interrupted. In order to make the operated period of the reverberation control relay *RC* 40 msec, the time constant of the system R3, P2, and C2 is made less than 40 msec by the closing time of the relays. This is accomplished by adjusting P2 until the operated period of the reverberation control *RC* relay is 40 msec.

In order to control the length of the transmitter pulse, the multivibrator consisting of the tube V3 and its associated components is used. A common cathode resistor R13 is employed to complete the feedback loop. The multivibrator exercises its control by applying a positive pulse to the screen of the transmitter tube through a cathode-follower stage. During the off period of this multivibrator, the plate current from terminal 5 to 6 is determined by the choice of tube type, the plate-load resistance R16 and the common cathode resistance R13. To drive the plate as near -300 v as possible, the voltage drop across R13 should be as low as possible, while, to maintain the bias on the 1-2-3 section of the tube sufficiently below cutoff to prevent false triggering, this voltage drop should be as high as possible. A workable compromise is achieved by the use of a 6SN7 tube with the values assigned to the plate and cathode resistors indicated in Figure 7. Triggering of this multivibrator is accomplished by a contact on the relay *RC* in the following manner. Between pulses, the left-hand end of C4 is charged to -105 v through the 100-megohm resistor R10. Closing the bottom contacts 1-2 of the relay *RC* grounds this point and produces a positive pulse on terminal 1 of V3 of approximately 18  $\mu$ sec duration and 105 v magnitude. Chatter of the relay contact in *RC* does not tend to cause false triggering due to the long time required to recharge the condenser C4. The 3-msec on period of this multivibrator is determined primarily by C6 and R15.

## 22.4

## TRANSMITTER

The transmitter consists of a self-excited class C oscillator which is keyed by applying a 3-msec positive pulse to its screen by means of the 3-msec multivibrator and a cathode-follower stage. A schematic of the transmitter circuit is indicated in Figure 8. The plate supply for the oscillator is 3,000 v obtained from a 7.5- $\mu$ f storage condenser which is charged during the intervals between transmitted

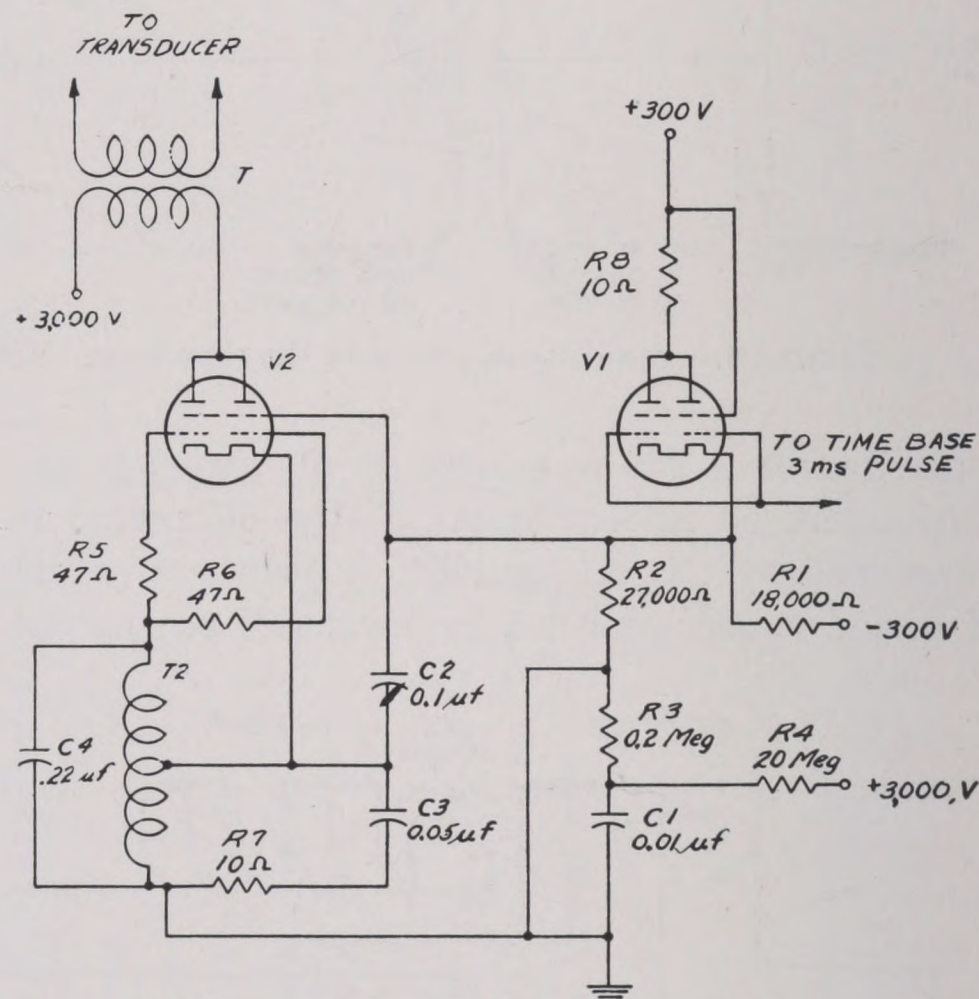


FIGURE 8. Transmitter circuit.

pulses by means of a high-voltage transformer and rectifier. The plate current of the oscillator tube V2 is approximately 1.33 amp during the 3-msec interval of transmission. The voltage across the storage condenser is reduced by approximately 20 per cent during this interval.

The frequency-determining element of the oscillator is a polystyrene-insulated condenser C4 and the inductance T2 which is tuned by means of a movable permalloy slug. Frequency stability is obtained by close coupling of the grid and cathode windings in the oscillator coil, and is further assured by the fact that the high plate resistance of the tetrode V2 is between the load and the frequency-determining element of the circuit.

During the off period, V1 is nearly nonconducting and the screens of V2 are biased at approximately -80 v. In practice it is necessary to do some selecting of the 3E29 tubes which are used for V2 in order to insure low enough plate current drain during the

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off period to permit the storage condenser to be charged to the proper voltage.

During the transmitting period, the 3-msec multivibrator applies a +300-v pulse to the grid of V1 which, acting as a cathode follower, supplies a pulse of about +250 v to the screen of V2. In the design of the oscillator, three factors had to be considered: frequency stability, time of pulse build-up and decay, and tank-circuit efficiency. An extremely high- $Q$  tank circuit results in high frequency stability and high tank-circuit efficiency but slow build-up time. However, the rate of build-up is also determined by the excess gain in the oscillator feedback loop. The constants for this oscillator were chosen as a compromise between these factors such that build-up and decay times of approximately 0.5 msec are realized. The resulting frequency stability is adequate to meet the overall requirements of the system.

## 22.5 TRANSMITTER-RECEIVER SWITCHING CIRCUIT

Since a single transducer is used for the functions of both projector and hydrophone, it is necessary to provide means of switching between transmission and receiving in order to prevent the receiver from being damaged during transmission and to prevent the transmitter from providing a load on the transducer during reception. Figure 9 shows a schematic of the switching system used, which consists of four thyrite elements, RV1, RV2, RV3, and RV4. These thyrite units have an impedance characteristic which varies in inverse proportion to the third power of the current passing through them. Thus RV3 and RV4 become low-resistance elements under the influence of the transmitter during the 3-msec transmitting interval and, therefore, serve to connect the transmitter transformer to the two transducer units connected in parallel. The voltage drop through the thyrite units during transmission is of the order of 100 v and, therefore, a negligible power loss is introduced. During the receiving interval when the signal voltages developed by the hydrophones are low, RV3 and RV4 become high-resistance elements and therefore serve to isolate the two halves of the transducer from the transmitter. In practice, because of the capacity of the thyrite units, their impedance cannot be considered to be so high as to have no effect on the receiving circuit. They provide a certain amount of coupling between the transmitter output transformer and the hydrophones, particu-

larly if the capacities of the two halves of each thyrite unit are unequal. This causes noise, originating in the transmitter transformer caused by either inductive pickup or ripple on the power supply, to be fed into the receiver. This factor is a serious limitation on the entire system since this source of noise may be the limiting factor in receiver sensitivity rather than the torpedo self noise.

The voltages applied to the transducer during the transmitting pulse would be damaging to the receiver input transformers if they were not prevented from reaching these elements. Isolation is provided for the starboard receiving channel by condensers C1 and C2 and the thyrite unit RV1 and for the port

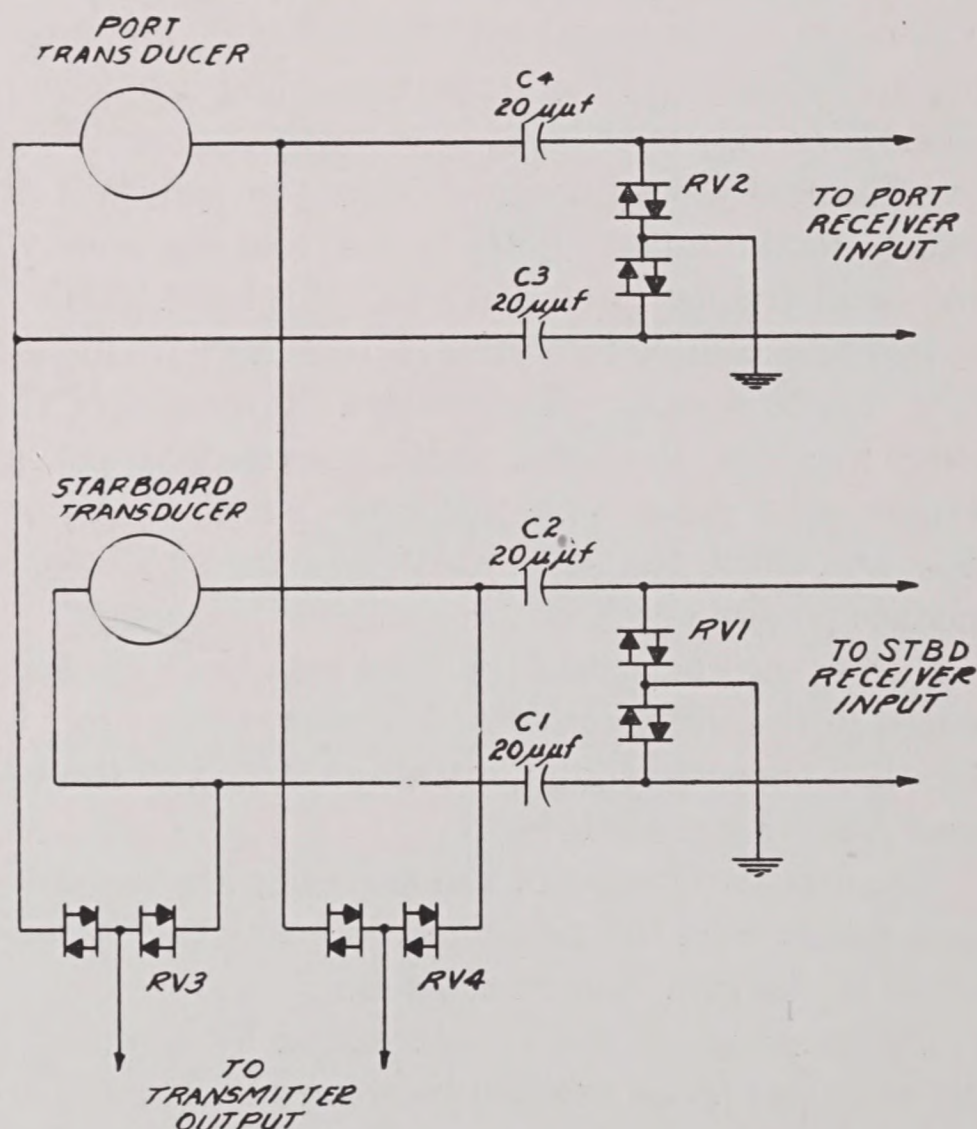


FIGURE 9. Thyrite switching system.

receiving channel by the condensers C3 and C4 and the thyrite unit RV2. During the time of transmission the thyrite units RV1 and RV2 become low impedance and therefore limit the voltage applied to the primaries of the receiver transformers to approximately 275 v. This is a sufficiently high magnitude to initiate transients in the entire receiver circuit, in spite of the presence of a blanking bias on the grids of the first two stages of the receiver. It is, however, sufficiently low to protect the transformers from insulation breakdown. During the receiving interval RV1 and RV2 are high-resistance elements, but they represent, nevertheless, shunt capacities across the

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## 22.8 VARIABLE GAIN-CONTROL FOR THE RECEIVER AMPLIFIER

The function of the variable gain-control circuit is to adjust the gain of the first two stages of the amplifier so that the level of output of the amplifier caused by noise and reverberation will be brought to a fixed level below the threshold. By so doing, any signals are amplified as much as possible without danger of reverberation or self-noise signals passing the threshold stage. Since the signal is composed of reverberation, which is a decaying factor, and self

ence of signal at the output of the third amplifier stage is sufficient to assume control. For the remainder of the 1-sec listening interval, the gain variation is under the control of the signal output of T9 which is a winding in the output transformer of the third stage of each amplifier.

The receiver gain-control is separate for the right and left receiver channels. A schematic of the circuit used is shown in Figure 11. For times less than 32 msec after transmission, corresponding to a range of 24 yd, the sensitivity of the amplifier is essentially zero because of the operation of the relay *ST*. For

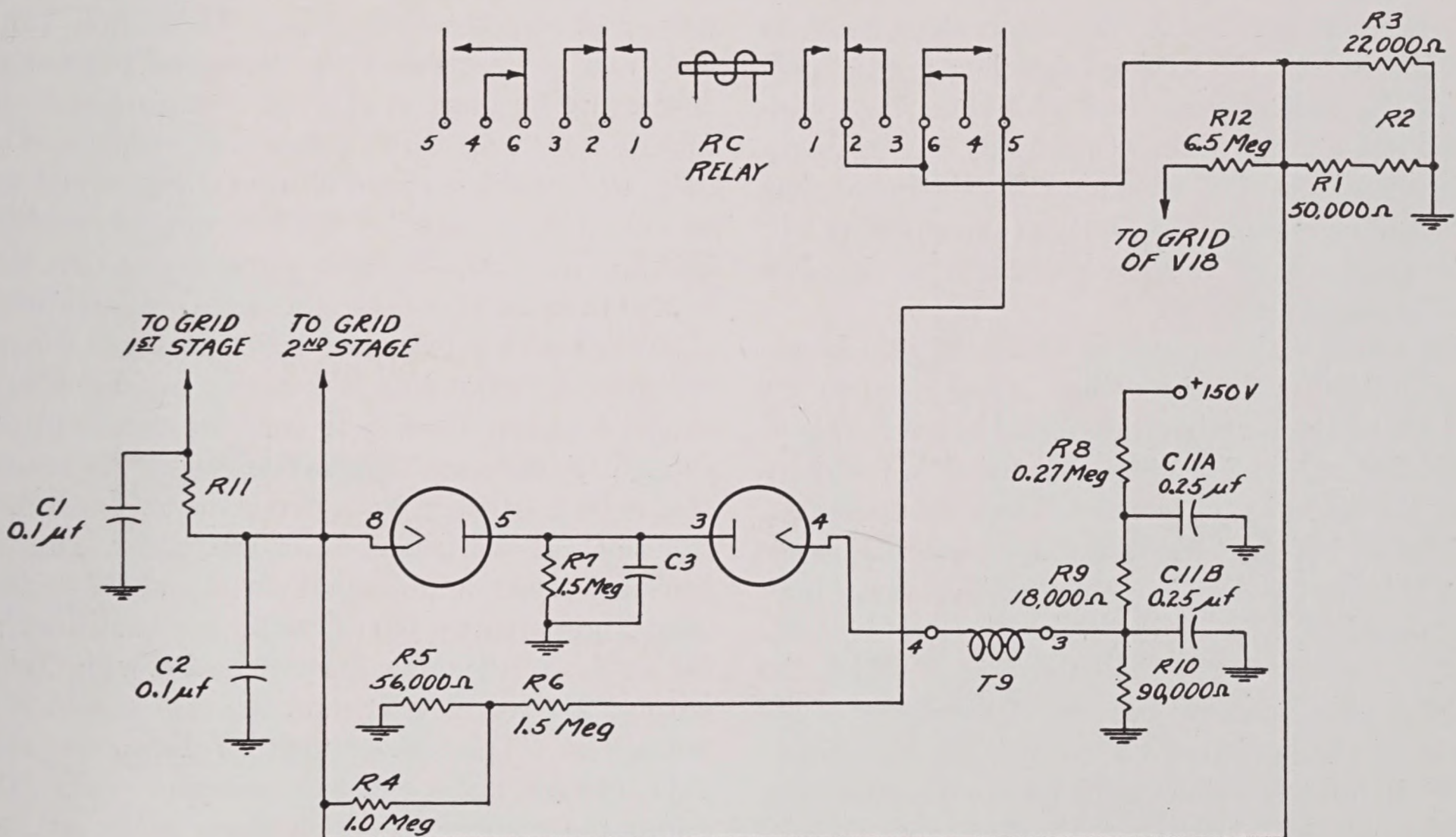


FIGURE 11. Variable gain-control circuit.

noise, which is a relatively steady factor, the gain-control circuit is set up so that the gain is always increasing or held constant; i.e., it cannot decrease during a listening period.

The gain control should not be confused with the disabling of the circuit during and shortly after transmission. While the gain is held to a minimum during the disabling period, the actual disabling is accomplished by the relay *ST*, indicated in Figures 7 and 10, at a point further on in the circuit.

At a time 40 msec after transmission, the gain of the receiver begins to increase under the control of the gain-control circuit, rising rapidly at first at a rate of approximately 24 db for double time intervals and continuing to rise at this rate until the pres-

the next 8 msec the gain of the amplifier remains constant, since contacts on the relay *RC* maintain the voltage on C1 and C2 at -5.25 v. This voltage is derived from the -105-v regulated supply through the divider resistors R1, R2, and R3. The voltage on these condensers supplies bias to the grids of the first two amplifier stages. When the relay *RC* opens, the condensers C1 and C2 begin to discharge through two parallel paths: one, through resistors R4 and R5 and two, through the 8-5 section of the diode and R7. The reduction in voltage on these condensers causes the gain to increase until it reaches a value such that the output signal from the amplifier is sufficient to produce a voltage across the 3-4 winding of T9 having a peak value equal to or greater than



the sum of the following two factors. One, the bias supplied to terminal 3 of T9 from the voltage divider consisting of R8, R9, and R10 and, two, the voltage existing on C3. When this voltage is exceeded, current will flow between terminals 3 and 4 of the diode causing terminal 3 to become negative with respect to ground by the amount by which the peak value of the output of T9 exceeds the first of the above bias factors. This voltage established across C3 and R7 prevents discharge of the condenser C2 through the diode path. Since the voltage on C2 may now decay only through R4, the rate of gain increase in the amplifier is reduced so that its maximum value now will be about 9 db per double time-interval. It must be remembered that the received signal during the portion of the receiving interval which has been considered will normally consist primarily of surface reverberation. The time constants are chosen so that the rate of increase in sensitivity of the amplifier will not be great enough to allow reverberation signal to pass the threshold stage.

Now consider the manner in which the gain is controlled following the time when it has risen to the point where the reverberation signal has first caused conduction of the 3-4 section of the diode and reduced the rate of gain increase. From this point on, until the end of the 1-sec listening period, the operation will be as follows. The reverberation signal may be expected to decrease in level with time. If it decreases at a rate faster than the rate at which the amplifier gain increases, because of the decay of the voltage of the condenser C2 through R4, the output at T9 will fall to a value insufficient to cause conduction through the 3-4 section of the diode and the voltage on C3 will decay through R7 until conduction through the 8-5 section of the diode is reestablished. When this happens, the gain will again increase at the rapid rate until the output level again rises to a point where the rapid gain increase is blocked. This type of control continues until the level of reverberation signals falls to a value less than the signal caused by the self noise of the torpedo. The system is so designed that the amplifier gain cannot increase to a point where the expected self noise of the torpedo will produce a signal which can pass the threshold stage.

So far, the performance of the gain-control circuit under the influence of reverberation and noise has been discussed. The action will now be considered in the presence of an echo signal. It has been observed that echo signals often consist of a smear of echoes

representing signal returning from many points over a range of 50 yd or more. The value of signal necessary to cause conduction in the threshold stage is approximately 7.2 db greater than the value necessary to produce conduction in the 3-4 section of the gain-control diode. The latter is determined by the bias applied to terminal 3 of T9. The 7.2-db differential is the value which field experience has indicated to be the minimum value necessary to exclude noise peaks. The lowest possible value is used in order that the minimum level of signal above the peak background noise will be passed by the threshold circuit. It is obvious that when the signal level exceeds the noise and reverberation voltage, conduction will occur in the 3-4 section of the diode and prevent further rapid increase in gain. If it were not for the feature which permits further slow increase of the gain, the maximum level of echo smear would need to exceed by at least 7.2 db the value of the reverberation at which the gain increase was first interrupted in order to pass the threshold. In other words, if a smear echo is received at short range at the time when the reverberation is decaying rapidly, it is desirable to allow all of it to pass the threshold even though the distance attenuation causes the last portion to be less than 7.2 db greater than the reverberation level at the beginning of the smear. The time constant of the combination of C3 and R7 is determined primarily by the following consideration: The 3-4 section of the diode in combination with C3 constitutes a peak rectifier, and the rate at which the voltage on C3 decays through R7 during the intervals between noise and reverberation peaks determines the manner in which these peaks are integrated. The voltage on C2 decays only during the minimums of the voltage on C3. Therefore, the more rapidly C3 is allowed to decay the lower it will fall between noise peaks and the lower the final voltage on C2 will become. The choice of a time constant of 15 msec for the C3 and R7 combination is one of the factors determining the choice of 7.2 db as the voltage ratio. Any change in the time constant would necessitate a new choice for the voltage ratio.

## 22.9

### LIMITER CIRCUIT

The limiter circuits following the threshold stages are conventional, single-stage, high-gain, class A amplifiers. The limiting action is achieved simply by virtue of the fact that the signals applied to this stage are such that overload occurs when the voltage

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output of the threshold stage is only 1 db greater than that necessary to pass the threshold. This is due to the fact that a 6SH7 tube overloads at approximately 3 v of signal on the grid, and 1 db above the threshold of 52.5 v is a 6.5-v signal. A series resistance limits the grid current in this stage to small values and, therefore, prevents the grid from going appreciably positive. This enhances the limiting action. When the signal level is 2 db above that necessary to pass the threshold stage, the limiter stage will be completely limited.

and 5-6 of F1 and 5-6 of F2 are all phased in the same way. This means that the voltages in 3-4 and 5-6 of F1 will always be in phase and the voltages in 5-6 of F2 will lead, be in phase, or lag those in F1, depending on whether the echo is received from the right, dead ahead, or left. Assume that an echo is received from the left, so that the right-channel signal in 5-6 of F2 lags the left-channel signal in 3-4 and 5-6 of F1 by 45 degrees. These voltages are indicated in vector diagrams in Figures 13A, B, and C. The vector representing the voltage in 5-6 of F2

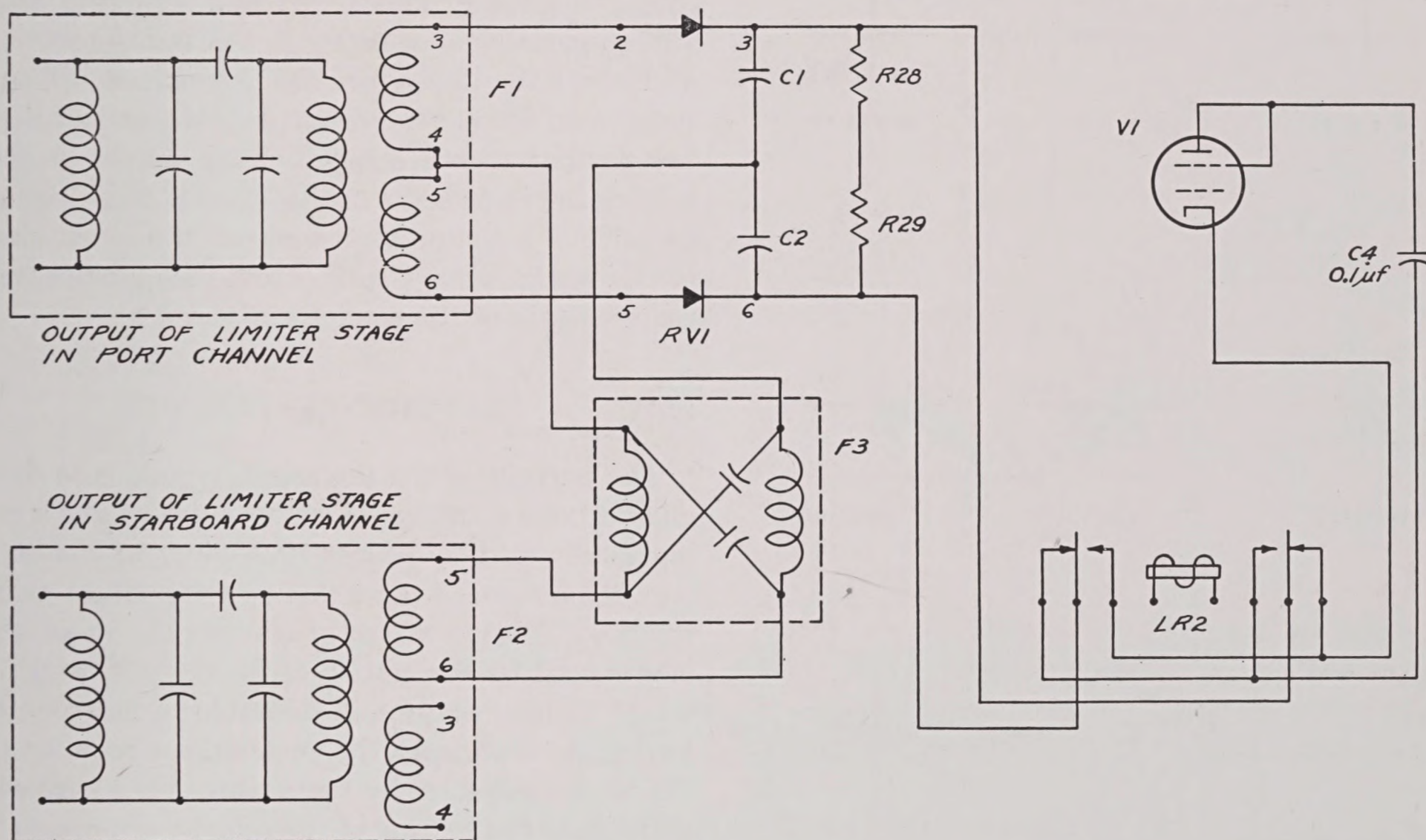


FIGURE 12. Phase-sensitive detector.

## 22.10 PHASE-SENSITIVE DETECTOR

It is the purpose of the phase-sensitive detector to combine the output of the two receiver channels in such a way that the difference in electrical phase between them can be used to generate a usable signal. The essential elements of the detector are shown in Figure 12. F3 is a 90-degree phase-shift network and RV1 is a rectifier. The triode V1 and the condenser C4 retain the information, which consists of a d-c voltage whose sign depends on the direction of incidence of the echo signal on the transducer and whose magnitude depends on the value of the angle between the torpedo axis and the direction of the incident echo signal.

In the operation of the circuit, the windings 3-4

will be delayed 90 degrees by the phase-shift network F3 so that the vector representing the voltage in 3-4 of F3 will be as indicated in Figure 13D. Referring to Figure 12, it will be noted that the voltage  $A + C'$  is rectified by section 2-3 of RV1 and applied across the resistance R28. Similarly the voltage  $C' - B$  is rectified and appears as a voltage across R29. These voltages will be added vectorially as indicated in Figures 13 E and F. When rectified, the relative magnitudes of voltage appearing across R28 and R29 can be indicated as in Figure 13G. The plot of voltage at the top end of R28 referred to the lower end of R29 as a function of electrical phase angle is indicated in Figure 13H.

When an echo is received, V1 is made conducting so that the condenser C4 which was previously



charged to +19 v is discharged to the value appearing across R28 and R29. The following three factors determine the choice of values of R28, R29, C1, C2, and RV1. First, the storage condenser C4 reaches its final voltage through a series-resistor circuit consisting of the plate impedance of the tube V1 and the load resistances R28 and R29. The sum of these components must be sufficiently small to allow C4 to reach its final voltage within 1 msec. This determines the maximum value for R28 and R29. Second, the

decay of the detector pulse. The rapid rise of the rectified pulse is determined by the size of the condenser C4, the impedance of the varistor, and the impedance of the source supplying the detector circuit. The source supplying the detector circuit is the plate circuits of the limiter stages whose impedance is modified by the filters F1, F2, and F3 and by the ratio of the output transformers F1 and F2. The transformer ratio is determined by the output voltage required from the detector, which is 30 v for a maximum phase difference of 90 degrees at the input. With this value determined and with the limiter tubes operating at saturation, the transformer ratio and hence the impedance are determined. The impedance of the varistor elements is chosen sufficiently low so that they are not limiting factors in determining the impedance of this circuit. It is necessary to achieve a compromise between the quick charge of the condensers C1 and C2 and the quick-charging requirements of the condenser C4.

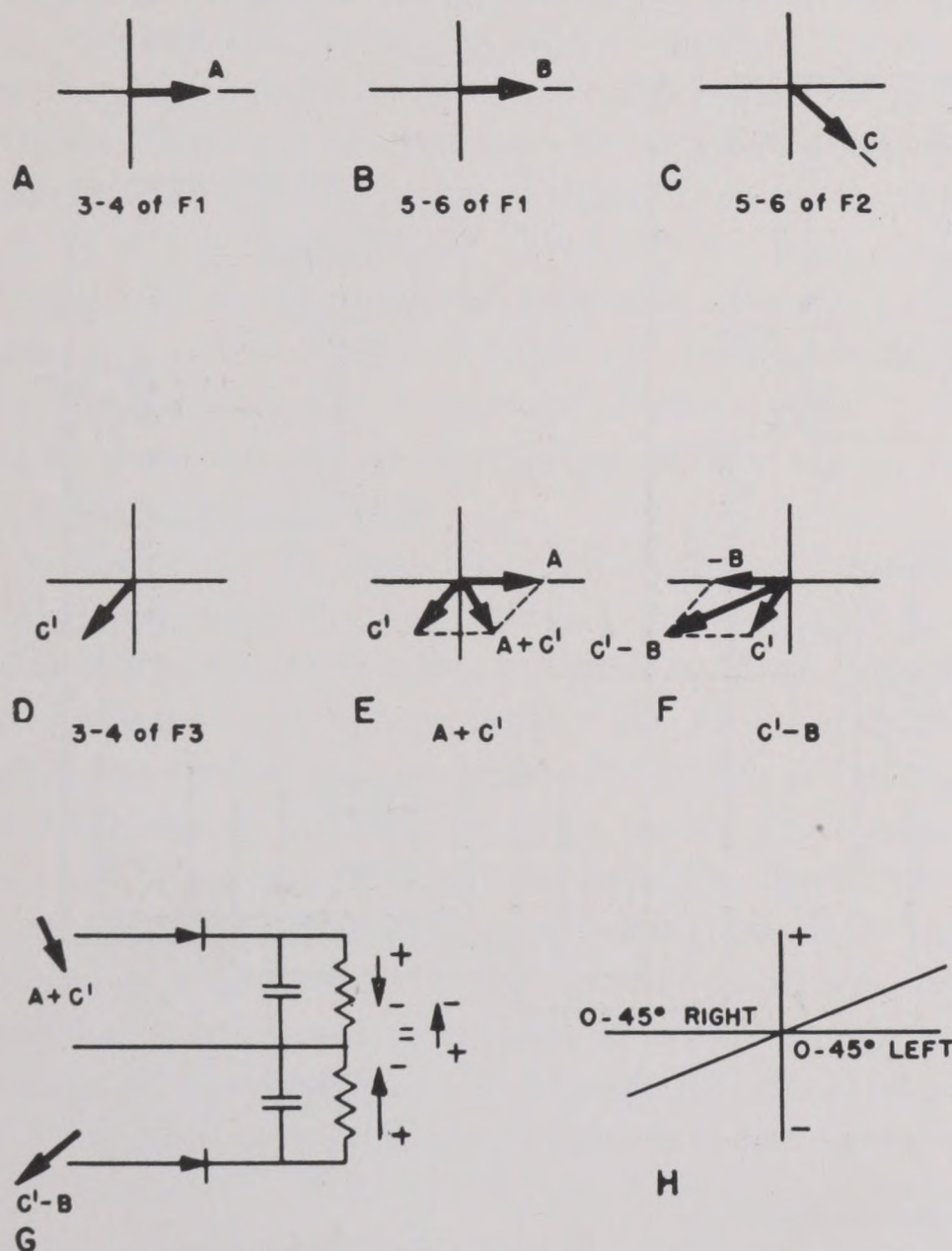


FIGURE 13. Analysis of phase-sensitive detector operation. (Refers to Figure 12.)

condensers C1 and C2 act as filter condensers for removal of signal frequency from the echo pulses. The degree of filtering is a function of the ratio of the condenser impedance at signal frequency to the load resistance. The value of the capacitance is so chosen that 30 db of suppression of signal frequency voltage is obtained. Third, it is necessary that the shape of the rectified pulse shall be such that the final voltage is reached quickly. It is also necessary that following termination of the received signal, the pulse will fall off sufficiently slowly so that the grid of the tube V1 can be biased to cutoff before the voltage on C4 is appreciably modified because of the

## 22.11 PREFERENCE CIRCUIT

The purpose of the preference circuit is to distinguish among a number of echoes coming from a moving target, and by proper presetting, to choose the one which comes from a point on the target nearest the bow. This is a means of ignoring the wake which is produced by the motion of the target through the water. It has been found desirable to incorporate a lead-angle feature in the preference circuit so that the course called for by the setting of the gyro cover plate leads the bearing of the echo by approximately 4 degrees. The actual value of the lead angle can be varied from 0 to 8 degrees by proper circuit adjustments. The circuit elements involved in this feature are shown schematically in Figure 14. The ability to choose the rightmost or leftmost echo is achieved by means of the phase-sensitive detector V1, the relay LR2, and the condenser C4 which stores the output of the phase-sensitive detector. In operation, the condenser C4 is charged at the beginning of each listening period to +19 v. When an echo passes the threshold circuits this condenser will be discharged to a voltage equal to the output voltage of the phase-sensitive detector. If succeeding echoes are received, the value of voltage assumed by the condenser C4 will be equal to the new value of the phase-sensitive detector output voltage providing this voltage is negative with respect to the previous signal. The fact that the tube V1 conducts in only one direction



prevents the potential of the condenser C4 from being changed in a positive direction. The relay LR2 indicated in Figure 14 is used to connect the phase-sensitive detector to the condenser C4 so that either port or starboard echoes will make the potential of the top of the condenser more negative. The system is preset for preferred-side steering, by setting up the relay LR2 so that echoes from the preferred side make the top of the condenser C4 most negative.

voltage equal to that applied to the cathode circuit by the output of the phase-sensitive detector. At the termination of the echo signal V1 is again cut off so that further discharge of the condenser C4 is prevented. A later signal, less positive than the preceding one, will repeat the sequence and permit the voltage on C4 to fall to a still lower value. However, a succeeding signal more positive than the preceding one will not alter the voltage of C4 since, in this case,

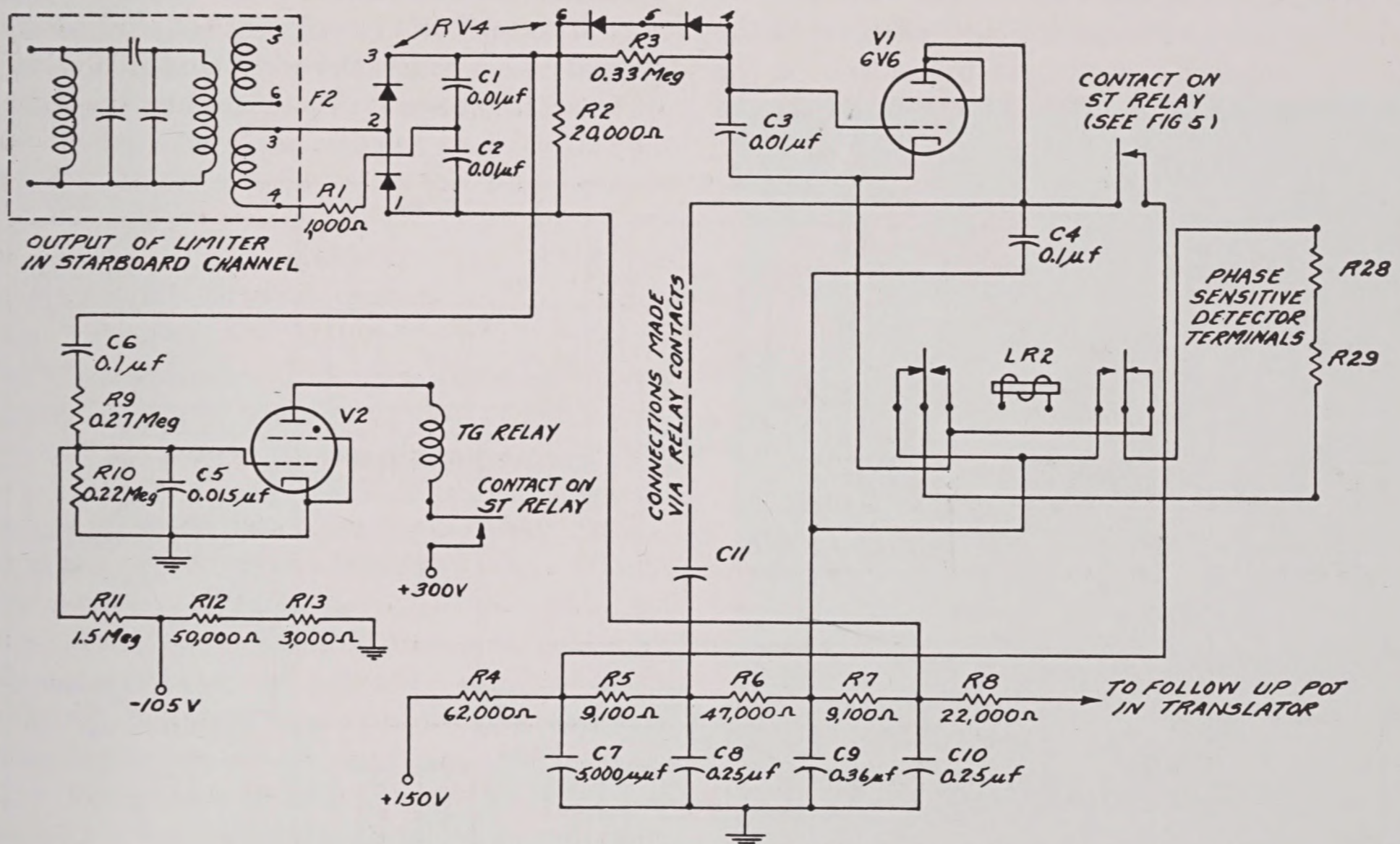


FIGURE 14. Preference circuit and trigger circuit.

The operation of the system is as follows. The condenser C4 is charged by means of a contact on the relay ST to +19 v with respect to its terminal which goes to the junction of R6 and R7. It is prevented from discharging in the absence of echo signals by V1 which is biased to plate-current cutoff by a suitable tap on the voltage divider consisting of the resistors R4, R5, R6, R7, and R8 and the follow-up potentiometer in the translator. The output of the phase-sensitive detector, which is developed across the resistors R28 and R29, is connected in the desired sense through the contacts of the relay LR2 between the cathode of V1 and one side of C4. When an echo signal passes the threshold circuit, and after a suitable delay which is introduced in the trigger circuit, the grid of V1 is driven positive. The condenser C4 is then free to discharge through V1 to a

the cathode of V1 will be positive relative to its plate and the tube will not conduct in that direction. The manner in which the grid of V1 is driven positive will be explained under Section 22.12.

The value of the condenser C4 is determined as a compromise between two factors. First, a discharge time constant of approximately 0.2 msec is required. This determines the maximum size of C4. Second, it is necessary for the circuit leakage resistance to be very high. It is essential that the voltage due to charge stored on C4 shall be capable of remaining unaltered by circuit leakage for a period of 1 sec. This determines the minimum size for C4 and also the minimum possible circuit leakage resistance including the leakage resistance of C4 itself. The circuit leakage is minimized by the use of a guard circuit which holds to a minimum the voltage drop across the leakage path.



## 22.12

## TRIGGER CIRCUIT

The trigger circuit, also indicated in Figure 14, performs two functions following the receipt of an echo signal which passes the threshold. First, it makes V1 conducting by removing its bias after the output of the phase-sensitive detector has reached equilibrium and reestablishes the bias at the proper time in relation to the output pulse from the phase-sensitive detector. Second, it fires the gas tube V2.

The first function of the circuit is achieved in the following manner: a portion of the output of the limiter in the starboard channel is obtained from the

ducting until the output of the phase-sensitive detector has had opportunity to reach its equilibrium value. It should be noted that the grid-to-cathode voltage of V1 is actually a composite of the trigger-circuit voltage and the phase-sensitive detector voltage. This is somewhat undesirable since an output of the phase-sensitive detector of such a polarity as to cause the cathode of V1 to become negative with respect to the junction of R6 and R7 will, in effect, reduce the bias on the tube and, therefore, tend to cause it to conduct in the absence of a trigger signal. However, in practice, the grid-to-cathode voltage of V1 from this source is also delayed by the combina-

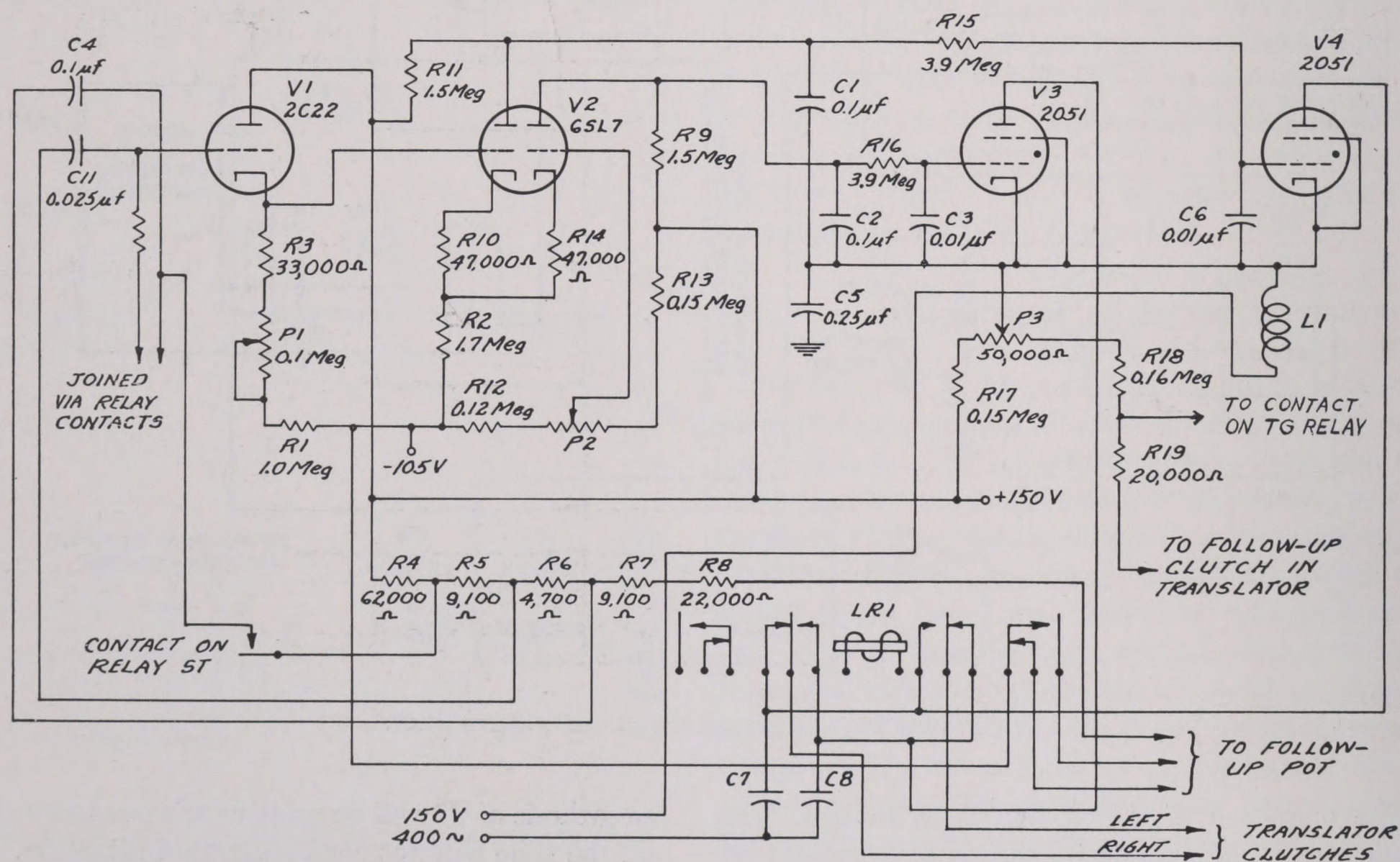


FIGURE 15. Servo system.

3-4 winding of the filter transformer F2. This is rectified in the voltage-doubler rectifier circuit consisting of the 1-3 arm of RV4 and the condensers C1 and C2 developing a voltage across the load resistor R2. The rate of rise of voltage across R2, following receipt of an echo signal, is somewhat faster than the rate of rise of the phase-sensitive detector output voltage across R28 and R29, because of the relative magnitudes of the condensers C1 and C2 and the source impedance. This voltage is applied to the grid of V1 through the resistor R3. The resistor R3 and condenser C3 serve to delay the rise of voltage on the grid of V1 so that the tube does not become con-

ducting until the output of the phase-sensitive detector has had opportunity to reach its equilibrium value. At the termination of an echo signal, the bias on V1 is rapidly restored to a negative value, since the condenser C3 discharges through the 4-6 arm of RV4 which shunts the resistor R3 for current flow in this direction. In this manner V1 is cut off before the phase-sensitive detector output voltage has fallen appreciably from its equilibrium value.

The second function of the trigger circuit, to fire V2, in turn operates the TG relay and so initiates a train of relay operations essential in the control of the torpedo. It has been found desirable to delay the

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firing of the tube V2 beyond the beginning of an echo signal by about 1.5 msec. This delay, introduced to make the circuit less sensitive to peaks of self noise of the torpedo, is accomplished through the action of the resistor R9 which is shunted by the resistors R10 and R11 and the condenser C5. The choice of a 1.5-msec delay is dependent on the choice of 7.2 db as the amount a signal must exceed the noise voltage in order to pass the threshold stage. The delay in the firing of the tube V2 is also associated with the delay in the reduction of the bias on the tube V1. These delays should be of approximately the same magnitude, since it obviously is undesirable for V2 to fire before V1 becomes conducting and modifies the voltage on the condenser C4.

22.13

## SERVO SYSTEM

The electromechanical system, following the C4 condenser shown in Figures 13 and 14, translates electrical information into mechanical rotation. The essential parts of this system indicated in Figure 15 are a d-c amplifier, two control gas tubes, a translator, and a follow-up potentiometer.

The voltage on C11 remains there for about the time required for maximum rotation of the gyro cover plate. The high side of C11 is connected to the grid of V1, a coupling stage, which was selected for its very high input resistance to prevent the charge on C11 from leaking off. The low side of C11 is connected to a voltage divider between +150 and -105 v which also contains the follow-up potentiometer in the translator. When the follow-up potentiometer is centered, the voltage at this point is zero.

The two halves of V2 and the thyratrons V3 and V4 are connected as two parallel d-c amplifiers, one of which operates on a positive signal on grid terminal 1 of V2, and the other operates on a negative signal on grid terminal 1 of V2. The plates of V3 and V4 are connected through relay contacts to the right and left rudder clutches in the translator in series with 150-v, 400-c alternating current. The potentiometer P3 sets the normal grid bias on these tubes so that for 0 v on C11 and the follow-up potentiometer in mid-position, they are extinguished.

With the system set for right preference, an echo from the left produces a positive voltage on C11. This breaks down V3 in the following way. Referring all potentials to the junction of R1 and R2 which is at -105 v, when the positive voltage on C11 makes

the grid of V1 positive the current in the cathode circuit increases, whereupon the grid 1 of V2 becomes more positive because of the drop in R3. This increases the cathode current in the 1-2-3 half of V2. Because of the drop in R2 the cathode of the 4-5-6 section becomes more positive, which reduces the drop in R9 and makes the grid of V3 more positive, causing it to fire. When V3 breaks down, it energizes the left gyro clutch which is located in the translator. A right echo produces a negative voltage on C11 which breaks down V4 in a similar fashion.

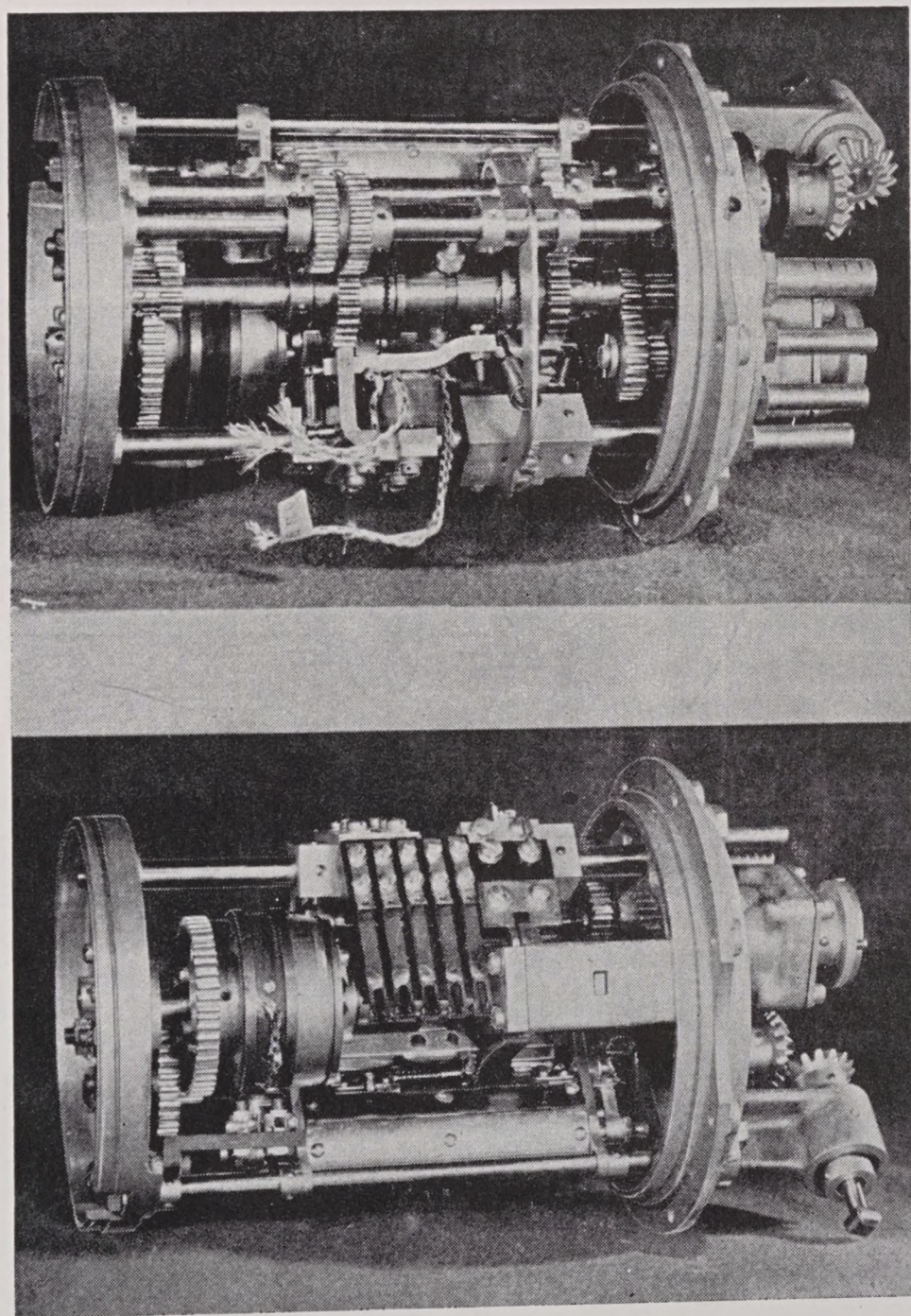


FIGURE 16. Translator with cover removed.

The construction of the translator and its coupling to the generator and power supply are shown in Figures 16 and 17.

The main drive for the translator is obtained from the driveshaft via the generator. Left and right gyro cover plate corrections are obtained by means of a pair of jaw clutches operated by a differential solenoid. One-half of each clutch is free-running on the shaft and is driven continuously and in the opposite direction from the corresponding half of the other

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clutch. The other two halves are in one piece and are splined to the shaft.

The operation of one of the control tubes V3 or V4 energizes the solenoid in one direction, engaging one of the jaw clutches and causing the translator shaft to rotate in the desired direction. Through gear trains, this rotation is transferred to the gyro cover plate. The shaft driving the gyro cover plate is on the side of the immersion gear which is shown in

of correction which can be applied to the cover plate by one operation. Another cam makes a contact when the shaft is in a position corresponding to the centering of the potentiometer. The heart-shaped cam, driven by a spring-loaded arm, returns the shaft to its center position when the potentiometer clutch is de-energized. This signifies that the translator is ready for more information. The other two cams are not used.

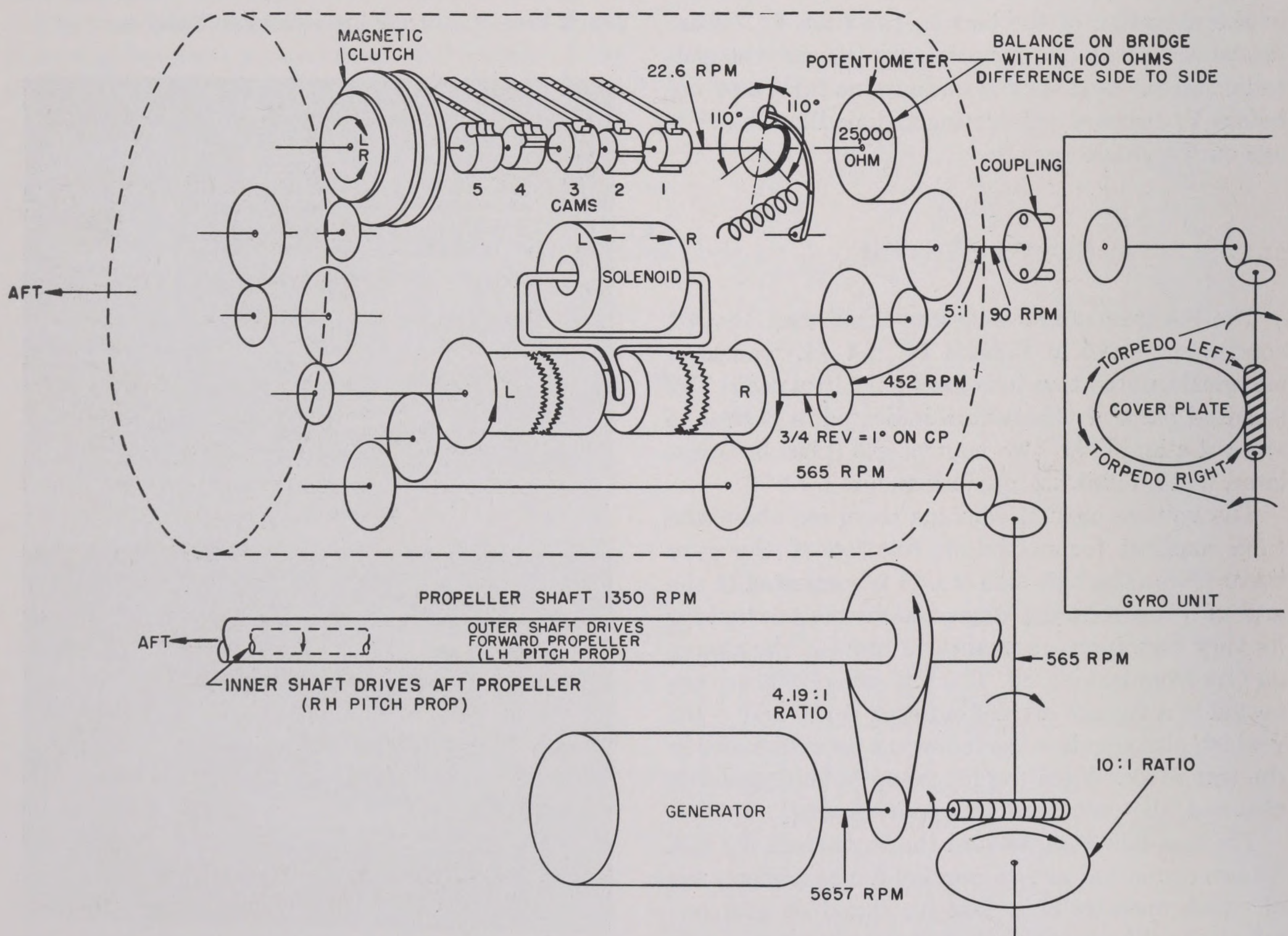


FIGURE 17. Schematic drawing of the translator.

Figure 18. The gyro cover plate switch is also shown in this picture. Its principal function is to limit the maximum excursion of the cover plate. It also contains the preference preset switch which is operated by turning the cover plate manually through the side-setting gear.

The translator shaft also drives, through a magnetic clutch, the cam shaft on which the follow-up potentiometer is mounted. Two cams on this shaft are used to operate switches that limit the amount

When an echo is received, the operation of a relay energizes the follow-up potentiometer clutch and, as the cover plate drive rotates, the potentiometer follows along with it. Taking as an example an echo coming from the left with the circuit set for left preference, V3 in Figure 15 becomes conducting and energizes the left gyro clutch which causes the cover plate drive to turn in that direction. When the follow-up potentiometer goes off-center in that direction it introduces a voltage between the low side



of C11 and the cathode of V1. When this becomes equal to the positive voltage on the high side the net effect is the same as zero voltage on C11, and V3 is extinguished. In this way the cover plate drive satisfies the demand of the condenser.

The same procedure would occur if an echo came from the right except that the high side of C11 would become negative, V4 would break down, and the right gyro clutch would engage and turn the potentiometer so as to put a positive voltage on the low side of C11. This would balance the negative voltage on the high side and would extinguish V4.

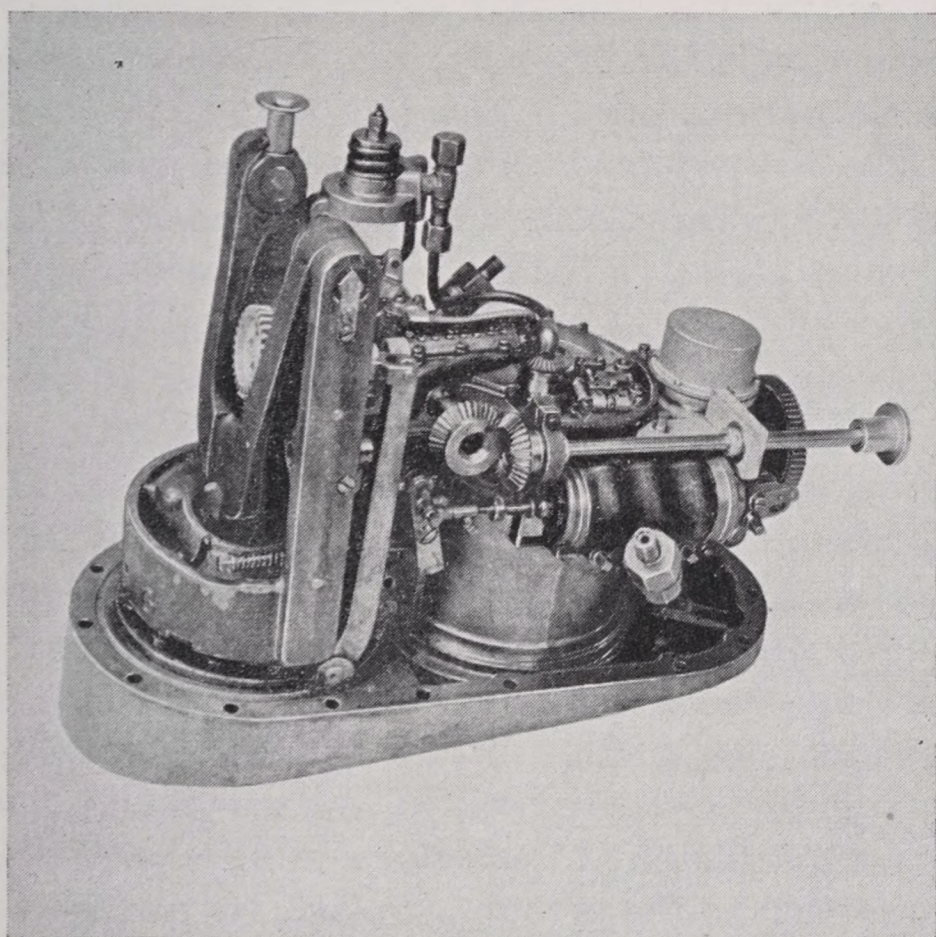


FIGURE 18. Modified immersion gear showing method of driving gyro cover plate from translator.

The whole servo system may be considered as an electromechanical amplifier employing negative feedback from the follow-up potentiometer to the grids of V3 and V4. The phase relations, however, are not adjusted to the point where sustained oscillations are suppressed. Because of the delay between the signal which operates the clutches and the turning of the potentiometer which opposes the signal, there is a tendency to oscillate or hunt at a frequency of about 2 c. This hunting can be observed in the right and left clutch lights on the recorder traces when no echoes are being received.

#### 22.14 RELAYS AND OVERALL SYSTEM OPERATION

The naming of the relays has been selected as an aid in understanding their functions. *RC* means re-

verberation control relay, *ST* means starting relay, *TG* means trigger relay, and *PC* means follow-up potentiometer centering relay, since it operates following the closure of the contact which is closed only when the follow-up potentiometer is centered.

These relays do not constitute all of the relay functions employed in the operation of the panel; however, in combination they accomplish all of the functions associated with the utilization of echoes when once they are received. The functions which they accomplish are in general not accomplished by one relay alone; hence, three relays will be discussed as a group and not separately. The functions which this group of relays serve to accomplish are eight in number:

First, to charge C4, Figures 14 and 15, to +19 v at the time the signal is transmitted.

Second, to short-circuit C11, Figures 14 and 15, thus eliminating any accumulated charge during periods in which no echoes are being received.

Third, to release the follow-up potentiometer clutch and hence permit the follow-up potentiometer to center, following the receipt of an echo signal.

Fourth, to transfer the voltage from C4 to C11, Figures 14 and 15, following receipt of an echo signal and closure of the follow-up potentiometer contact.

Fifth, to apply cutoff bias to the clutch-control tubes V3 and V4, Figure 15, during the period when the potentiometer clutch is de-energized, thus preventing the clutches from being operated while the potentiometer clutch is de-energized.

Sixth, to disconnect C4 from C11 at the end of a receiving interval during which the voltage was transferred from C4 to C11. This allows the voltage to remain on C11 during the succeeding receiving interval.

Seventh, to remove the plate-supply voltage for V2, Figure 14, which flows through the *TG* relay winding at the end of each receiving interval. This serves to extinguish V2 at the end of each receiving interval provided it has been fired by an echo received in that interval.

Eighth, to delay the transmission of the succeeding pulse until the follow-up potentiometer contact is centered, provided an echo has fired V2, Figure 14, prior to the end of the receiving interval.

The manner in which the above functions are used to provide operation of the preference circuit and to pass the information to the d-c amplifier will now be described with reference to a set of typical operating conditions.



In general, all normal functions of the torpedo may be subdivided into three groups of typical conditions. First, the system is operating but no echoes are being received; second, the echoes are being received regularly in each pulsing interval; and third, the performance of the system following the receipt of an echo which in turn is followed by a pulsing interval in which no echo is received.

For the consideration of the first condition in which the system is operating but no echoes are being received, the action of the relays is as follows: Relays *TG* and *PC* remain released at all times, C4 and C11, Figures 14 and 15, are not connected together, and the follow-up clutch is continuously engaged. Gas tubes V3 and V4, Figure 15, are enabled and the follow-up potentiometer will be hunting about the center position as discussed under the d-c amplifier. The *ST* relay operates once each second and performs the following functions. It connects C4 to +19 v, short-circuits C11, Figures 14 and 15, removing any leakage charge that might tend to build up at this point, operates the *RC* relay, which in turn charges the TVG condensers C1 and C2, Figure 11, and triggers the 3-msec multivibrator. It will be remembered that the latter controls the transmitter. All of these functions repeat once each second.

For the second condition, in which echoes are being received in each pulsing interval, assuming that no echoes have previously been received and the discussion is begun just prior to the transmission of the pulse which is to produce the first received echo, the functions are as follows: The operation of the *ST* relay charges C4 to +19 v, shorts C11 to remove any accumulated charge, and operates the *RC* relay to charge the TVG condensers and trip the 3-msec transmitter pulse. The *ST* relay releases approximately 31 msec after the transmitted pulse. This enables the *TG* relay, opens the charging connection to C4, removes the short from C11, and removes power from the reverberation control relay. C4 and C11 are disconnected from each other as previously noted. (Figures 14 and 15 should be referred to in discussion involving C4 and C11.) Approximately 40 msec after the transmitted pulse, the *RC* relay releases, its power having been removed by the release of the *ST* relay. This allows discharge of the TVG condensers to begin. The system is now in condition to receive an echo which will be assumed to arrive at some time between 40 msec and 991 msec after the transmitted pulse. When this echo arrives and passes the threshold, voltage from RV4 in Figure 14 fires

the trigger tube V2 and operates the *TG* relay. Simultaneously, the voltage on C4 is modified by the action of the phase-sensitive detector and the discharge tube V1. Operation of the *TG* relay performs the following functions: C11 is shorted, V3 and V4 in Figure 15 are disabled, since the common point of R18 and R19 which was previously grounded through a back contact of the *TG* relay is now free from ground, so that +300 v is supplied through the follow-up clutch, and R19 biases the cathodes of V3 and V4 to approximately +140 v. This same operation also disengages the follow-up clutch, because of the high resistance of R17 and R18 inserted in the clutch circuit. Additionally, the *TG* relay disables the *ST* relay to prevent the possibility of its operation until the next step to be mentioned has had time to be completed. The disengagement of the follow-up clutch allows the follow-up potentiometer to be centered if it is not already in that position. Centering of the follow-up potentiometer closes a contact energizing the *PC* relay. The operation of the *PC* relay performs the following functions. The *ST* relay is re-enabled; the short is removed from C11, and C4 and C11 are paralleled (Figures 14 and 15). V3 and V4, Figure 15, are re-enabled and the follow-up clutch re-engaged by re-establishment of ground on the junction of R18 and R19. Paralleling of C4 and C11 places a control voltage on C11, and the d-c amplifier and translator act to translate this information to the gyro cover plate. No further action occurs until the next normal operation of the *ST* relay, whereupon the function is as follows, and differs in important respects from the operation when no echoes were being received: The *TG* relay is de-energized; the *PC* relay, however, is held operated through its own 1-2B contacts and the 5-6B contacts of the *ST* relay. C4 and C11 are disconnected from each other and C4 is recharged to +19 v. C11, however, is not shorted as it was when no echo was received. This difference is achieved by virtue of the fact that the *PC* relay is now in the operated position. The *RC* relay is operated, the TVG condenser is charged, and the pulse transmitted as in the previous sequence. Upon release of the *ST* relay all the functions are the same as in the preceding sequence except that the *PC* relay is also released. Operation from this point on will be identical to the above operation as long as echoes continue to be received regularly in each pulsing interval.

For the third and final condition, in which following the receipt of an echo which in turn is followed



by a pulsing interval in which no echo is received, the functions are as follows. Begin the consideration with the operation of the *ST* relay which is closed during the time a pulse is transmitted for which no echo is received. In this case all of the operations of the *ST* relay are the same as were noted for the case in which echoes were being received, and, following its release, the voltage on C11 remains unaltered from that value which was placed on it by the echo received in the previous interval. The translator has presumably acted to translate this voltage to a corresponding angle on the gyro cover. Since no echo is received during this receiving interval, the *TG* relay does not operate. Hence, upon the next operation of the *ST* relay, the following operations occur: Since the *TG* and *PC* relays have not been operated, C11 is shorted, but the follow-up clutch is not re-

leased. In order for the follow-up clutch to be released the relay *TG* must be operated and the *PC* relay not operated. The rotation of the follow-up potentiometer due to the preceding voltage on C11 now produces an unbalanced condition at the input to the d-c amplifier and action of the amplifier and translator is initiated to restore a condition of balance. This requires a rotation of the follow-up potentiometer back to zero to balance zero voltage on C11. Hence the rotation previously translated to the gyro cover is now removed. All other operations of the *ST* relay are similar to those which occurred in the first condition described where no echoes were received.<sup>a</sup>

<sup>a</sup> See references 48-57 for additional material on topics in this chapter.



## Chapter 23

# GEIER TORPEDO CONTROL SYSTEM

### 23.1

### INTRODUCTION

AT THE end of 1942 the Atlas Werke, Munich undertook the development, under the code name *Boje*, an acoustic homing control system for torpedoes employing echoes received from the target ship rather than ship's noise. Tests conducted at Obertello, Italy, showed that, for distances of a few hundred meters, the echo-to-reverberation ratio is independent of range and depends only on the directivity index of the transducers. It was therefore decided that transducers having a high directivity index should be employed. In order to achieve this high index it was necessary to use a high frequency for the signal generator. There was a demand for a quick solution to the problem so, since Atlas Werke possessed only one standard nickel lamination transducer design operating at a frequency greater than 25 kc, namely a 77.5-kc unit, rather than tool up to produce nonstandard laminations, it was decided to use 77.5 kc. It was thought simpler to use separate projectors and hydrophones than to switch the output-input circuits to a single pair of transducers. Hence the space allotted to each transducer was severely limited.

By the end of 1943 the first laboratory models had been completed and tested against stationary and moving targets at Gdynia. After a few changes resulting from these trials, a preproduction design was frozen and designated as Geier 1. The first trials of this model were held in March 1944. Subsequently about 120 Geier 1 units were produced and most of them were installed in torpedoes. A few of these units were nonstandard, various modifications of the steering mechanism being tried. By the end of 1944 several hundred experimental torpedo shots had been fired at Gdynia.

In the meantime, it was decided to incorporate all the changes shown to be desirable by the Geier 1 trials in a new version, Geier 2. It was intended that Geier 2 be the service torpedo; Geier 1 was to have been the guinea pig. The development of Geier 2 was shared between Atlas Werke, Munich and Minerva Radio, Vienna. The first Geier 2 sea trials were held in the fall of 1944 and, by the time ac-

tivities were halted, about 20 experimental shots of Geier 2 had been fired. Shortly before the surrender of Germany, about 100 of the preproduction Geier 1 torpedoes were transferred from experimental use to operational status. However, it appears that none of these torpedoes were fired in action as they were later located in a depot.

Although there are these two principal versions of Geier, and each of them exists in a number of slightly different designs since the final version had not been decided upon at the close of the war, all the designs operate on the same basic principle. The torpedo is equipped with two magnetostriction projectors and two hydrophones, all four units being of the same design. These transducers are mounted in the torpedo nose, in the manner shown schematically in Figure 1. The projectors are excited simultaneously

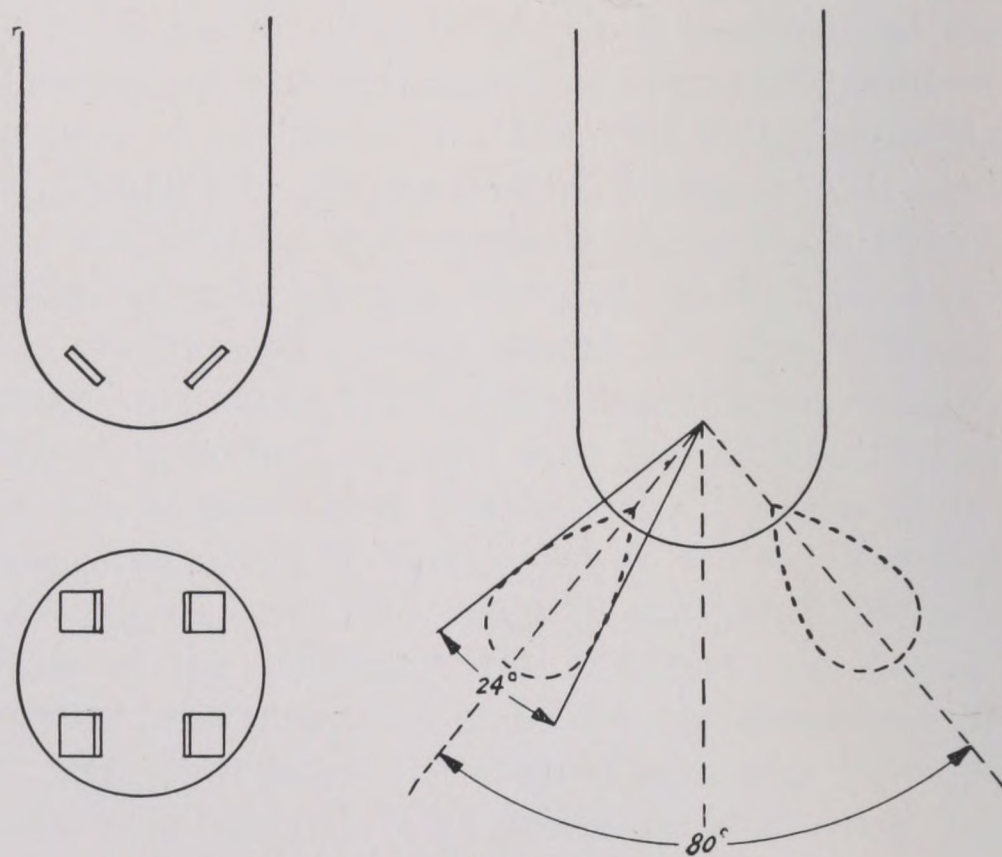


FIGURE 1. Geier transducer arrangement.

from the same source. Each hydrophone is connected to its own amplifier channel. There is no comparison of the intensities of the echoes received in the two channels; instead, each channel possesses a definite threshold, above the reverberation or background noise, which varies as a function of time after transmission and which the signal must exceed in order to exercise control. The steering method, which is of the cut-on cutoff type, exists in two variations, known



as symmetrical steering and preferred-side steering. When echoes are received on only one side, the two systems behave in the same way: the torpedo steers toward the echo side for a definite time and then returns to gyro control until another echo is received. In case echoes are received from both sides, the symmetrical steering system is governed by the first echo to arrive within a given ping interval. The preferred-side steering system is biased either to port or starboard just before the torpedo is fired, with the result that it always steers to the preferred side if an echo is received on that side, regardless of whether or not an echo from the other side has been received in the

and the latter probably the F5b. In both designs the transducers and electronic components are located in the torpedo nose. In the submarine torpedo the gyro assembly is equipped with solenoids in a manner similar to, if not identical with, the corresponding (*Specht*) system in T5. These solenoids are operated by relays in the forward electronic assembly. Power is obtained from a generator on the main propulsion shaft.

## 23.2

## GEIER 1

The application of Geier 1 to the submarine torpedo G7e had proceeded much further than the air-

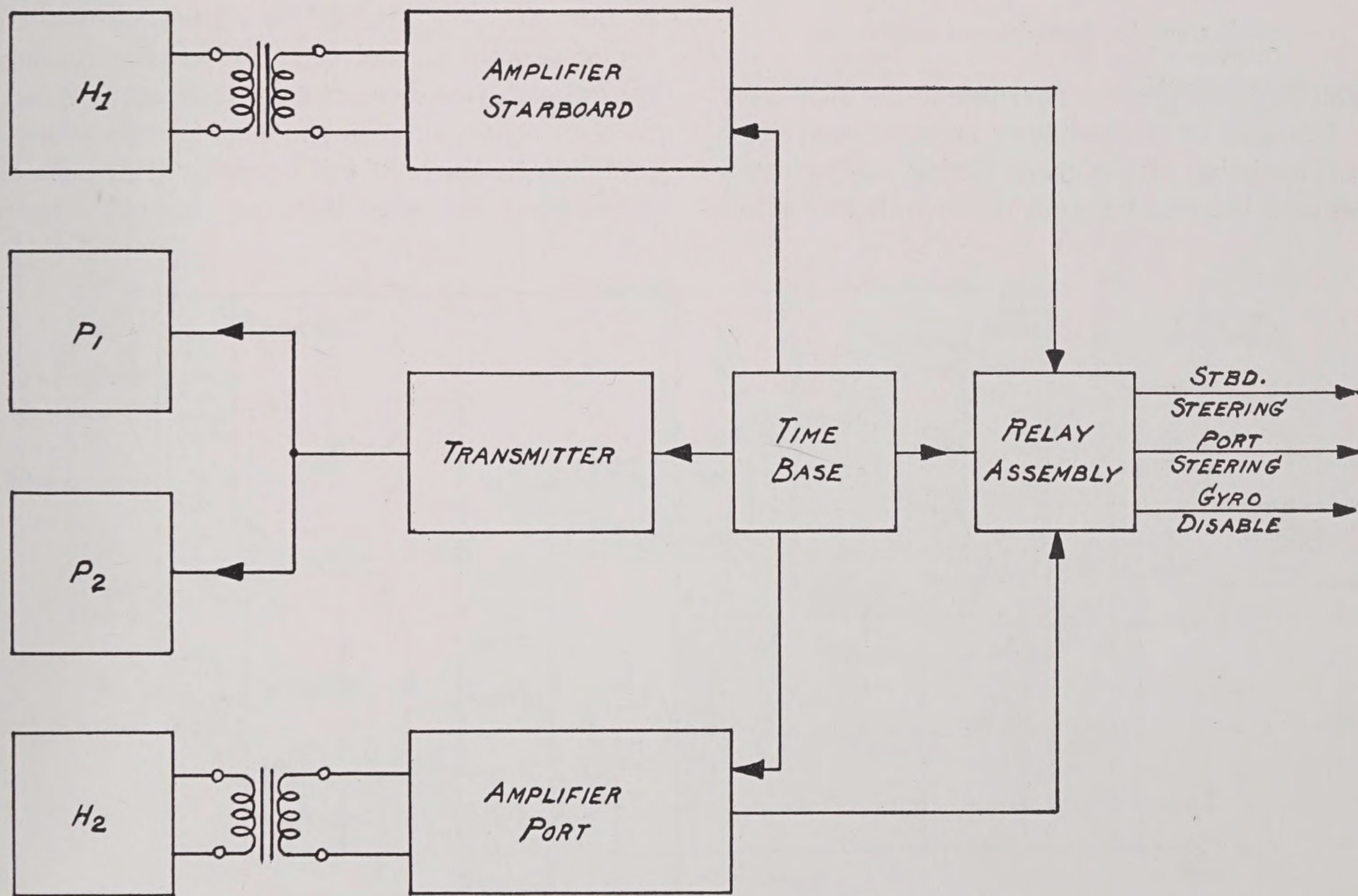


FIGURE 2. Block diagram of Geier 1.

same ping interval. The following specifications are common to all designs:

Frequency	77.5 kc
Pinging power electric input to each projector	100 watts
Ping interval	0.33 sec
Maximum reliable acoustic control range	200 meters

The Geier control was applied to both submarine and aircraft torpedoes, the former being the G7e

craft version. In the following paragraphs the submarine application is discussed in detail, and later the modifications for the aircraft version are noted.

The principal features of Geier 1 may be understood by reference to Figure 2. The projectors are excited by discharging a condenser through the winding. The condenser is connected to the projectors for a short interval by a contactor segment mounted on the rotating shaft of the mechanical time base. This shaft is driven by a small electric motor. After the condenser has discharged, it is disconnected from the



projectors and allowed to charge again from a high-voltage d-c power supply. Figure 3 shows the sequence of events during one ping interval.

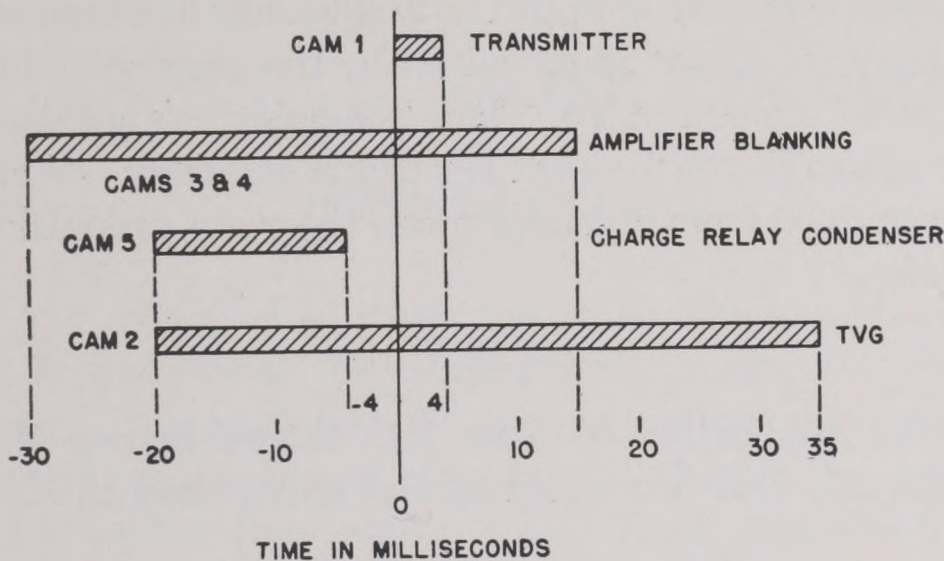


FIGURE 3. Time base of cams.

Each hydrophone is connected to its own amplifier. The gain of the amplifier is suppressed during the transmission of the ping; during the remainder of the ping interval the gain is controlled by a *time-*

torpedo steering engine. This assembly, which embodies the symmetrical-steering method, has two output channels. One of these operates a solenoid which disengages the gyroscope from the steering engine; the second channel operates solenoids which control the steering engine to give full helm to port or starboard. For example, if the torpedo receives an echo signal in the starboard channel, the gyroscope is disengaged and the helm put hard to starboard. The disengage relay is held in for 0.6 sec. If by that time no more echoes have been received in either channel, the disengage relay drops out and the torpedo returns to gyro control. If, after the first echo is received, another is received in the same channel in the next ping interval, the disengage relay continues to hold in, and the gyro remains disengaged for 0.6 sec after receipt of the last echo. When the torpedo comes close to the target or its wake, it is probable that echoes will be received in both channels during the same listening interval. The relay

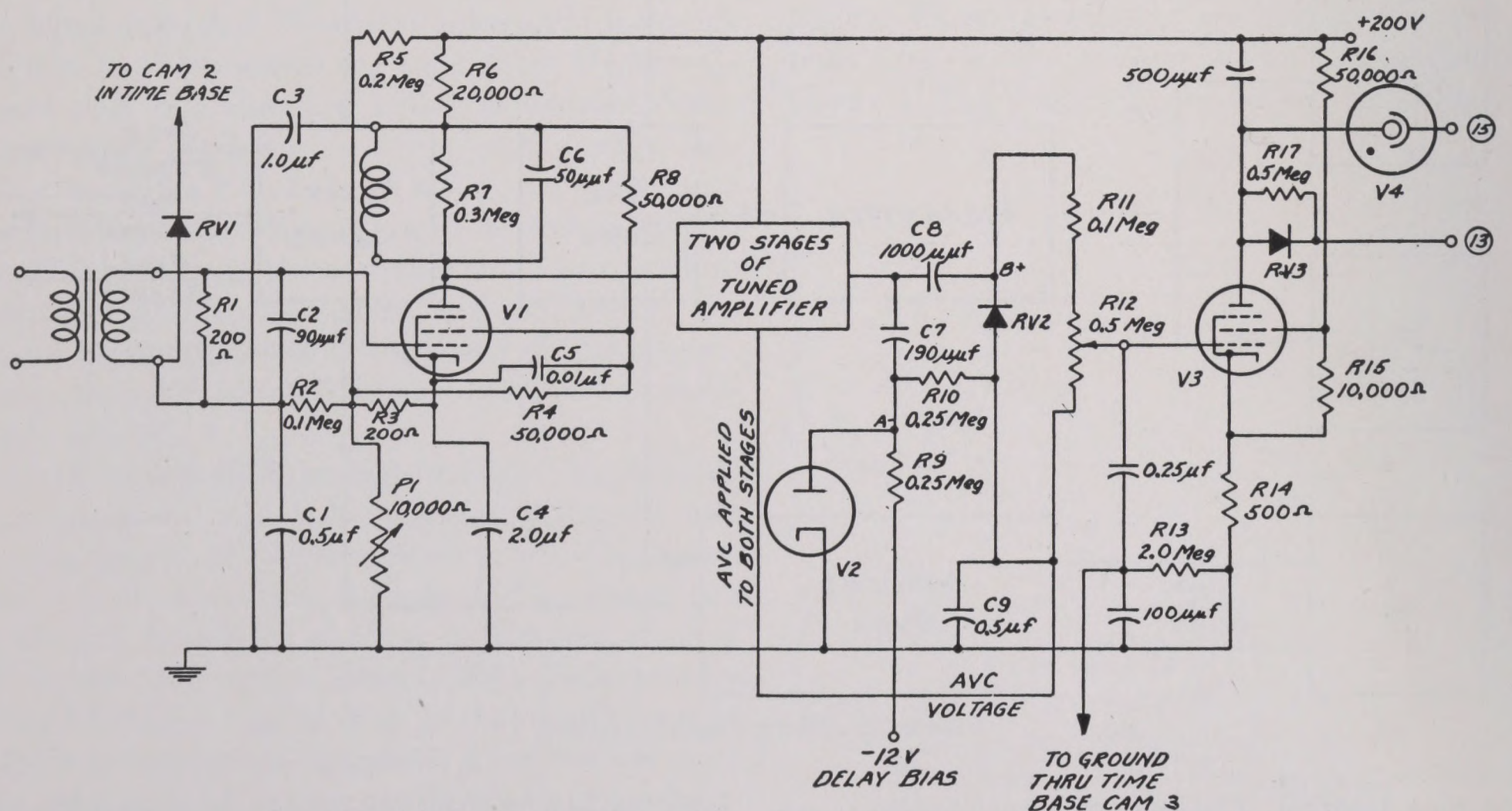


FIGURE 4. Amplifier showing TVG and AVC systems.

*varied gain* [TVG] circuit and a relatively slow-acting *automatic volume control* [AVC] circuit. The TVG circuit serves to reduce response to reverberation to a nearly constant level, while the AVC circuit corrects for differences in absolute level, such as those caused by torpedo roll and changing sea state.

The relay assembly is the connecting link between the electric signal output of the amplifiers and the

assembly includes a pre-emptive feature which permits it to ignore all signals other than the first which arrive within a given listening interval. Thus the torpedo tends to steer towards that part of the acoustic target to which it is closest.

Each transducer, resonant at the nominal frequency of 77.5 kc, consists of a rectangular block of nickel laminations slotted to provide space for the



winding. The radiating face is  $4.4 \times 8.5$  cm. The impedance at resonance is approximately 10 ohms. The four transducers, mounted as shown in Figure 1, are enclosed in a nose cap, or dome, made of a thermoplastic material. This dome is similar to or identical with the dome used in the round-nosed T5 listening torpedo. The space behind the dome is filled with ethylene glycol. The two-way transmission loss through this coupling system is stated to be 10 db.

The transmitter in Geier 1 consists simply of a  $1\text{-}\mu\text{f}$  condenser which is charged during the listening

mission. The condenser C4 is charged to a positive potential determined by the circuits consisting of P1, R3, R4, R5, R6, and R8. At the end of the 33 msec, cam 2 breaks the circuit between C1 and ground and C1 as well as the grid of V1 begin to approach the potential of C4 which is at the potential of the cathode of V1. This causes the gain in V1 to increase and the rate of increase in gain is controlled largely by C1 and R2. The setting of P1 determines the gain at the time of start of the gain increase.

The following two stages, indicated in Figure 4 in

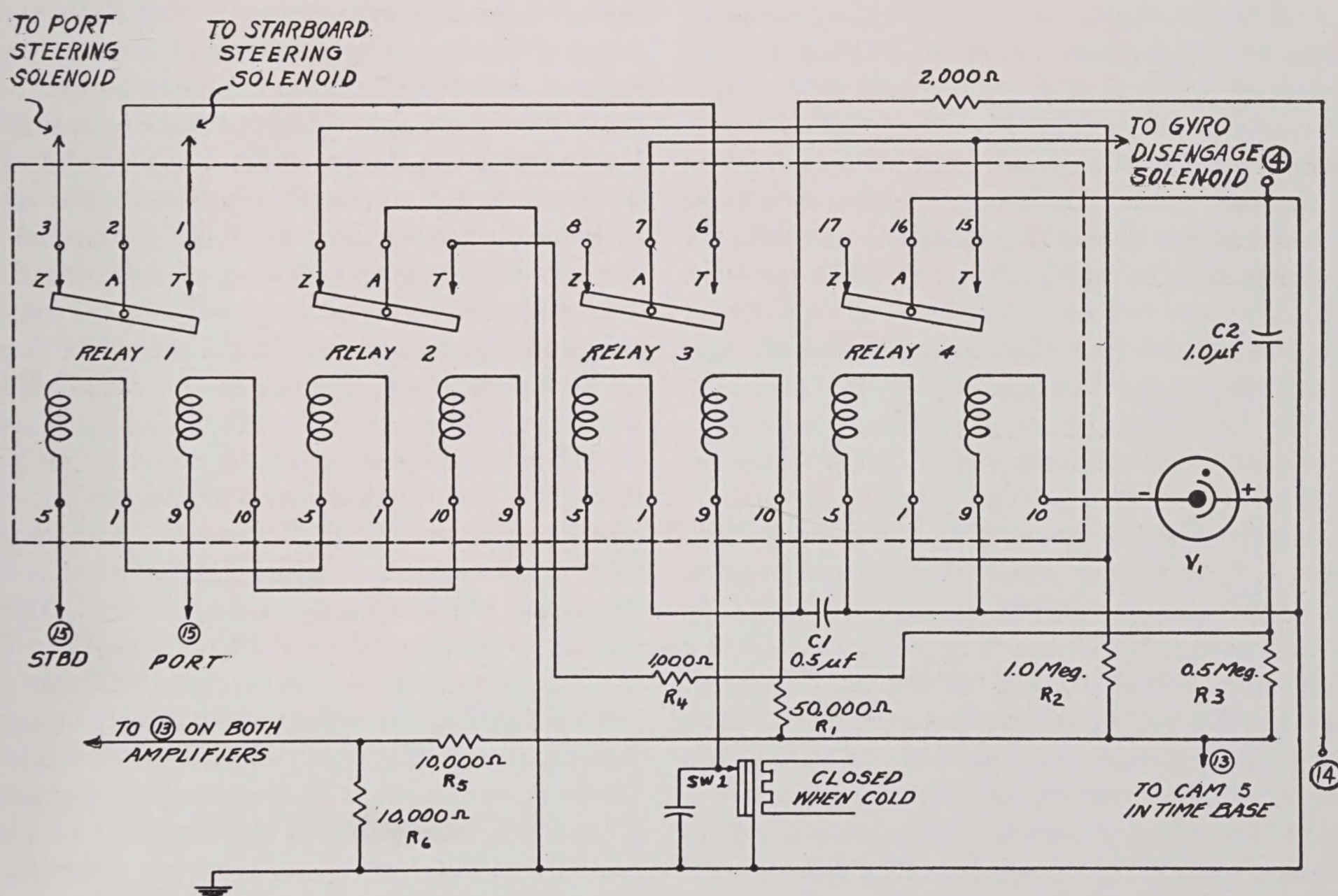


FIGURE 5. Relay system.

interval by means of a transformer and rectifier operating from a 36-c, 17-v a-c generator. The condenser is discharged through the tuned projectors by means of one of the cam switches in the time base.

The two receivers for the starboard and port channels are independent and identical. Figure 4 is a schematic of one of them. It consists of a 3-stage radio-frequency amplifier followed by a single stage pulse amplifier for operating the relays. The first stage V1 in Figure 4 is controlled by TVG. Cam 2 in the time base connects the grid of V1 and the condenser C1 to ground until 33 msec following trans-

mission. The condenser C4 is charged to a positive potential determined by the circuits consisting of P1, R3, R4, R5, R6, and R8. At the end of the 33 msec, cam 2 breaks the circuit between C1 and ground and C1 as well as the grid of V1 begin to approach the potential of C4 which is at the potential of the cathode of V1. This causes the gain in V1 to increase and the rate of increase in gain is controlled largely by C1 and R2. The setting of P1 determines the gain at the time of start of the gain increase.

When a signal appears at the junction of C7 and C8 it is necessary for it to have a peak value greater than 12 v before rectification can take place in the diode and the rectifier RV2. When rectification does take place, point A becomes more negative and point B becomes more positive and C9 acquires a further negative charge from point A via the resistor R10. This applies a greater negative bias to the grids of the



second and third stages of the amplifier which decreases their gain.

If the increase in signal level takes place slowly enough there will be very little change in the potential of the grid of the pulse amplifier V3 with the result that it will not become conducting. However, because of the long time constant imposed on the rate of development of negative potential by the condenser C9, a rapid increase in signal level will result in the grid of V3 becoming more positive. The exact conditions for firing V3 can be controlled by adjusting the potentiometer R12.

It will be noted that the plate of V3 is connected by way of the gas tube V4 shown in Figure 4 and the coils of relays 1, 2, and 3 in the control circuit shown in Figure 5 to the condenser C1. The condenser C1 is charged to +200 v just prior to the time the transmitter sends out its pulse. The voltage on this condenser is divided between the gas tube V4 and the plate of V3 in Figure 4. When a positive pulse arrives on the grid of V3 it causes V4 to break down and the condenser C1 in Figure 5 discharges through the relay coils and the plate circuit of V3. Once the discharge has started it will continue, using the rectifier RV3 as a return path even if V3 becomes cut off again.

The action of the relay assembly is as follows. Relays 1, 3, and 4 are polarized differential relays, whose armatures stay in the position to which they were last moved by a current impulse. Relay 2 is a spring-controlled relay which opens when no current is passing. Relay 4 is the gyro-disengage relay. When current passes through winding 9-10 the armature is in the Z position, which means the gyroscope is coupled to the steering engine. When current passes through winding 1-5, the armature moves to the T position, energizing the gyro-disengage solenoid. Relay 1 is the steering relay; when current has last passed through winding 9-10, the armature is in the Z position, energizing the port solenoid, and contrariwise when current has last passed through 1-5. Relay 3 is a relay whose contacts are in series with the power supply energizing all the solenoids. When current is passing through winding 9-10, the electrical steering is disabled. This circuit feature provides the delay in initiating acoustic control required for safety purposes. The delay is provided by the thermal delay switch SW1, which opens after a definite time. Relay 3 is operated to the other, or closed, position by the first signal impulse which arrives from either channel after SW1 has opened, and

remains in this position thereafter. Relay 2 is an intermediate relay whose armature is in the Z position when not operated by current.

Suppose now that the initial safety delay has elapsed, so that SW1 is open. Terminal 13 of the assembly is connected to the positive side of the 200-v supply, while terminal 4 is connected to the negative side of this supply. Relay 2 is in the Z position, shorting the 1-5 winding of relay 4. C2 charges through R3 until the gas tube V1 breaks down, sending a pulse of current through the 9-10 winding of relay 4. The period of this simple relaxation oscillator is 0.6 sec. Relay 4 stays in the Z position and the torpedo remains under gyro control. During the ping transmission, terminal 14 of the control circuit (*Veilchen*) is briefly connected to the 200-v supply by the last contactor on the time base (terminals 9 and 10). Thus C1 is charged to this potential. For the remainder of the ping interval C1 is disconnected from the high-voltage supply. If a signal, having sufficient amplitude to fire the glow tube V4 in the amplifier shown in Figure 4, arrives in the starboard channel, C1 discharges through the protective resistor R6 and windings 1-5 of relays 3, 2, and 1. Relay 3 is moved to the T or closed position and remains there for the rest of the run. Relay 2 moves momentarily to the T position and returns to Z after C1 is discharged; relay 1 moves to the T position, if not already there, energizing the starboard-steering solenoid. The momentary operation of relay 2 has two results. First, C2 is discharged, so that winding 9-10 of relay 4 will not receive another pulse until 0.6 sec has elapsed. Second, the short is removed from 1-5 of relay 4, so that a pulse of current passes, moving relay 4 to the T position. Thus the gyro disengage solenoid is operated, and the steering engine passes under the control of the starboard solenoid. If after 0.6 sec has elapsed no more echoes have been received, C2 will again discharge through the gas tube V1 and winding 9-10 of relay 4, thus restoring the torpedo to gyro control. On the other hand, if an echo is received in the next listening interval, before the 0.6 sec have elapsed, relay 2 is again momentarily operated to the T position, again discharging C2 and ensuring a further delay of 0.6 sec before the torpedo is returned to gyro control.

The purpose of supplying the firing voltage for the glow tube in the amplifier from C1 of the control circuit is to provide the pre-emptive feature mentioned above, whereby the circuit ignores all but the first echo in a given listening interval. Clearly, once



this condenser has been discharged as a result of the first echo, none of the relays may be operated again until C1 is recharged at the beginning of the next ping interval.

No records of the many experimental trial shots were available at Atlas Werke, but some general conclusions regarding the performance of Geier 1 were stated by Atlas personnel who had attended the trials. On bow shots the performance was good, but for shots made aft of the beam of the target, in many cases the torpedo attempted to home on the wake, crossing the latter at right angles. After doing so, it would return to gyro control and proceed away from the target. This result is in qualitative agreement with an analysis of the symmetrical type of steering, which is discussed in more detail in Section 23.4. It was stated that the gear was responsive to ship or decoy noise; in particular, the torpedo was said to be able to home on ship's noise at a range of 500 m provided the noise is modulated. If the noise is steady in level, then the only fluctuation appearing at the grid of the fourth stage of the amplifier is that caused by the increase of gain resulting from the action of the TVG circuit. Preliminary tests show that if a steady signal of single frequency is applied to the input circuit, this type of fluctuation is sufficiently slow so as to be very effectively removed by the action of the AVC circuit. On the other hand, if the ship's noise fluctuates rapidly, the peaks will not be suppressed by the AVC circuit and will appear like echo signals. Then, the only condition necessary for operation of the control circuit by such noise peaks is that they exceed the reverberation, or the steady average noise background, by the amount determined by the setting of potentiometer R12 in Figure 4.

Some difficulty was experienced with increased reverberation caused by torpedo pitch and roll. Since reverberation rather than self noise is the limiting factor in determining whether or not useful echoes are received, this problem was given serious consideration. A transducer assembly stabilized both in roll and pitch was developed.

The electronic circuits for the aircraft version are the same as those used in the submarine torpedo; but since the plastic nose used in the latter is too weak to withstand water-entry shock, a different design had to be produced for the aircraft torpedo. It was found very difficult to reconcile the requirements of mechanical strength and acoustic transparency. The first attempt consisted of mounting the trans-

ducers directly in the steel nose cap of the conventional torpedo, so that the radiating surfaces were in direct contact with the water. This arrangement was satisfactory from the strength viewpoint and of course provided the best possible coupling between water and transducers, since there was no intervening dome. However, such an arrangement does not permit the use of a stabilized transducer assembly. The problem of roll in the aircraft torpedo was even more serious than in the submarine type, so the use of such a stabilized array was considered essential. Lt. Col. Bree has indicated that the problem of roll stabilization of the aircraft-launched torpedo had been pretty well solved by the Luftwaffe at the end of the war although no Service torpedoes had been manufactured using this improved feature.

The aircraft version of Geier differed from the submarine type in one other respect; namely, the method of using the output signal of the amplifier to control the steering. Instead of disengaging the gyro and operating the steering engine by solenoid control, the signal caused the gyro to be angled by a small motor. When echoes ceased to be received, the gyro-angling motor stopped and the torpedo continued to run straight until another signal was received. Thus the aircraft-launched torpedo did not retain the original launching direction for its gyro course.

### 23.3

## GEIER 2

The Geier 2 circuit differs from the Geier 1 principally in three features. The first principal difference is that the projectors are excited by a power amplifier driven from a conventional oscillator which is keyed from the time base. Although this arrangement requires more components than the simple condenser discharge circuit of Geier 1 it has two distinct advantages over the latter system: First, the contacts on the time base which connect the projectors to the output amplifier are already closed when the oscillator begins, so that sparking is eliminated, and second, the transmitted pulse is much cleaner. The envelope is approximately square, as compared with the rapidly decaying exponential envelope produced by Geier 1. Because of better frequency control most of the transmitted energy is concentrated in a narrow band around the nominal operating frequency. Not only is this more efficient than the damped-oscillation type of transmitter, it is also more secure, since the pinging can only be detected by listening in the neighborhood of the central frequency.



The second principal difference is the addition of a noise discriminating circuit to the latter. The principle of this discriminator may be seen from the block diagram of Figure 6. After passing through four stages of amplification, the first three of which are controlled by a TVG circuit, the signal is passed through two filter channels. Channel *A* is a single band-pass filter whose mid-frequency is the transmitted frequency plus the average doppler shift expected to be encountered. Channel *B* is a double band-pass filter, having high attenuation at the echo frequency, the two pass bands being located symmetrically on either side. The output of each channel

the echo signal must be of at least the same order of magnitude in order to provide a reasonable differential between the two rectified voltages. However, in the relatively quiet periods between the noise bursts, a much smaller echo will be equally effective. Thus the circuit behaves as a rapid AVC circuit, with the added advantage that it can discriminate between noise and echo when the former has fluctuations comparable with the echo duration.

The third way in which Geier 2 differs from Geier 1 is in the functioning of the control circuits (*Veilchen*). Whereas the Geier 1 embodies symmetrical steering, Geier 2 employs preferred-side steering.

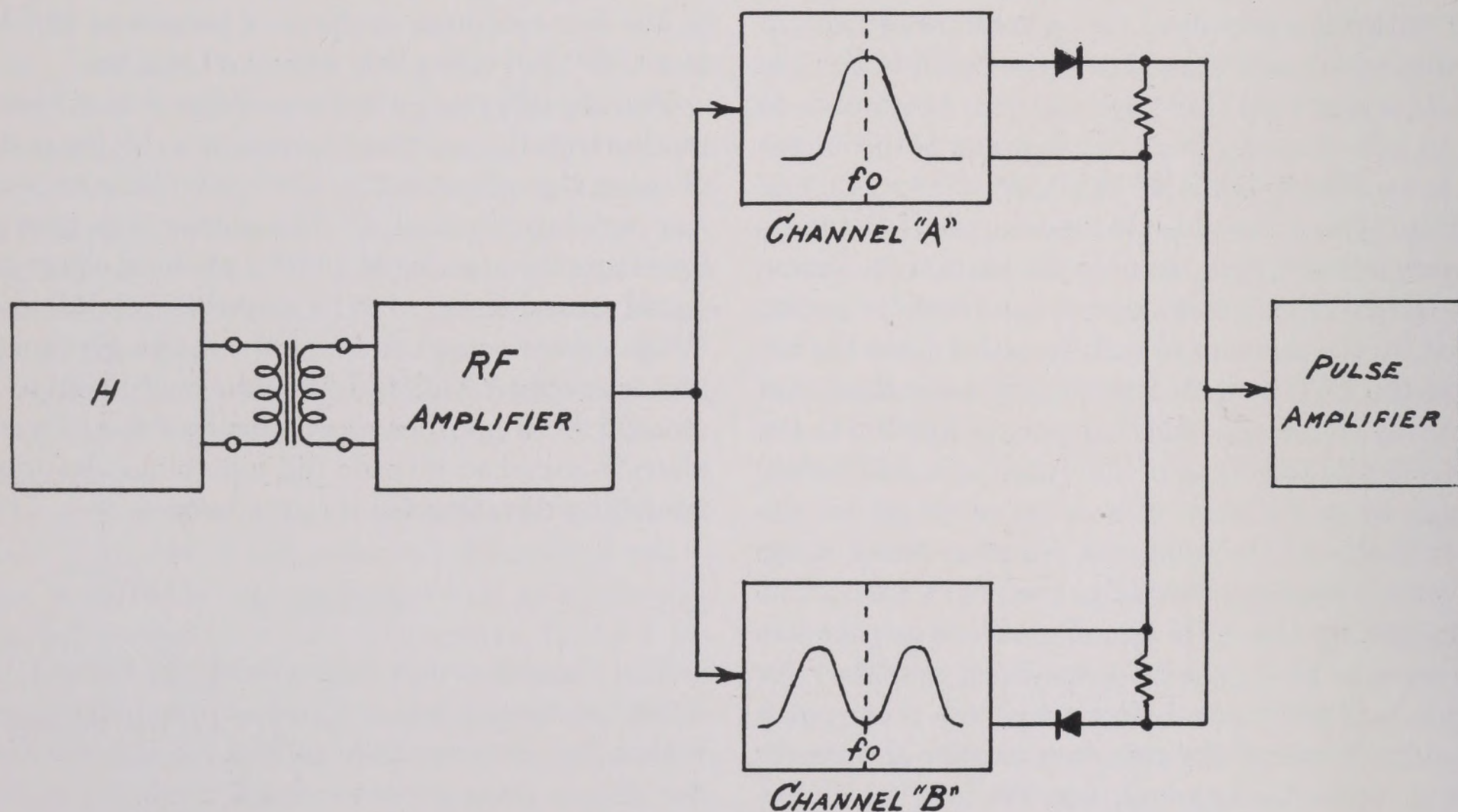


FIGURE 6. Discriminator.

is then rectified and these two rectified voltages are combined in opposite sense. The filter pass bands are so chosen that if white noise is fed into the system, the rectified voltages are equal and hence the resultant is zero. However, if an echo signal is present, it appears only in the single pass channel so that the rectified voltages are no longer equal. If the differential is greater than a predetermined threshold, the relay assembly is operated. The use of two pass bands in the noise channel permits the same result to be attained if the noise spectrum is not flat but has a constant slope in the part of the spectrum covered by the two channels. This noise discriminator is most effective against intermittent noise such as is produced by explosions. While the noise signal is present

The manner in which this is accomplished may be seen from Figure 7. This simplified diagram contains all of the essential features of the original control circuit shown in the Minerva Radio drawing of February 1, 1945.<sup>58</sup>

V1 and V2 represent the output tubes of the port and starboard amplifiers respectively. Relay 1, relay 2, and relay 4 are polarized differential relays. Current through winding 1-5 will operate the armature to the *T* position, and current through the 9-10 winding will cause it to move to the *Z* position. The armature remains on the side to which it was last moved after current ceases to flow. A differential of 0.3 ma is required between the 1-5 and 9-10 windings to cause the armature to move. Relay 3 is a spring-

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controlled relay which is operated to the *T* position on 0.6 ma through either winding and holds in on a current of 0.3 ma. When relay 3 is open, both the gyro-disengage solenoid and the steering solenoids are disabled. Relay 4 is the steering relay, causing either the port or starboard solenoid to be energized, when relay 3 closes.

A thermal delay switch, which closes after the initial safety delay, is placed in series with the 200-v supply to the relay circuits. Finally, the biasing circuit, controlled by the preferred-side switch, permits a steady current of 0.3 ma to be passed through either winding of relay 4.

of relay 1, so that the armature is immediately returned to the *Z* position, charging C1 again. Simultaneously C3 discharges through the 0.2-megohm resistor and winding 1-5 of relay 3. The operating current of 0.6 ma is reached during the very short interval in which C3 is being charged, but the minimum holding current of 0.3 ma is not reached until a considerable time afterward, on account of the long time constant of the discharge circuit. During this time interval, relay 3 is closed, so that the gyro is disengaged and the torpedo is under control of the steering solenoids. Since relay 4 is already in the port position, the additional current which flows through winding 1-5 pro-

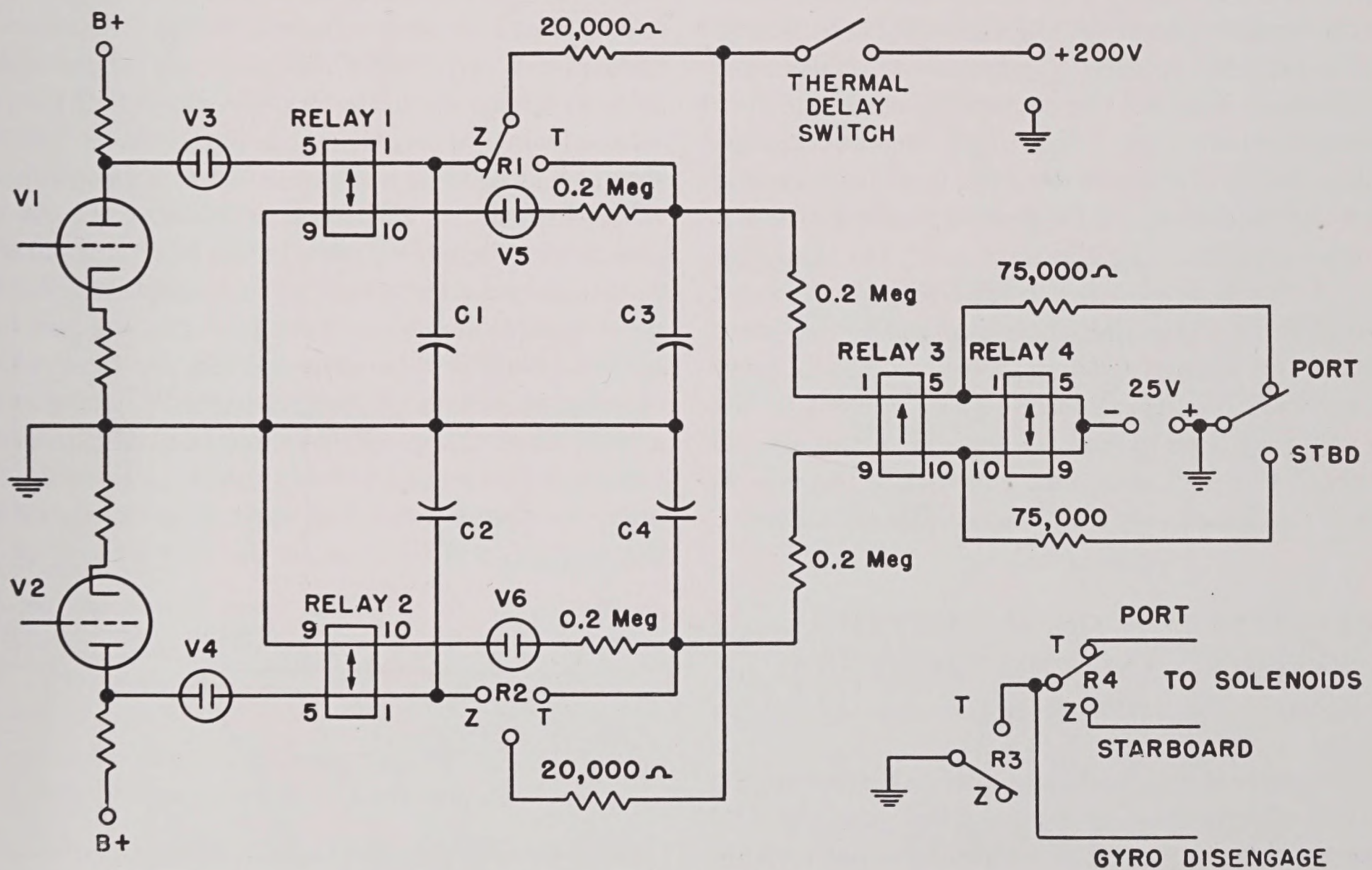


FIGURE 7. Preference circuit.

Suppose now that the initial delay has elapsed, the thermal switch has closed, and the preferred-side switch is in the port position. Relay 3 is open and relay 4 is in the port position, since the preferred-side switch is set to this side. Relay 1 and relay 2 are both in the *Z* position, so that C1 and C2 are charged to 200 v. Suppose now that a signal arrives in the port channel. V3 fires, discharging C1 through winding 1-5 of relay 1. The armature of relay 1 moves to the *T* position, and C3 is rapidly charged to the firing voltage of V5. When V5 fires, C3 begins to discharge through the 0.2-megohm resistor and winding 9-10

duces no action, and the torpedo rudder is put hard aport. After 0.4 sec has elapsed, C3 has discharged sufficiently so that the current through winding 1-5 of relay 3 drops below 0.3 ma; relay 3 then returns to the open position, the steering solenoids are disabled, and the torpedo returns to gyro control.

Next, consider the sequence of events when an echo is received in the starboard channel. C2 is discharged, momentarily operating relay 2 to the *T* position, charging C4. C4 then discharges through the 9-10 winding of relay 2, operating relay 2 to the *Z* position and also through the 9-10 windings of relays



3 and 4 operating relay 3 as before. The initial value of the current through 9-10 of relay 4 exceeds 0.6 ma, so that the differential between 9-10 and 1-5 of this relay is greater than 0.3 ma, and the armature moves to the starboard position. Thus the torpedo steers to starboard under solenoid control until relay 3 drops out, re-engaging the gyro.

Thus far, the preferred-side control duplicates the action of the symmetrical control used in Geier 1. Now consider the behavior when echoes are received in both channels in the same listening interval. If the first echo is from port, relay 3 is operated and relay 4 is moved to the port position, causing the torpedo to steer. A short time later, the starboard echo comes in, and current also flows through windings 9-10 of relay 3 and relay 4. Relay 4, however, remains in the port position because the current through the 9-10 winding cannot exceed the total current through winding 1-5 by the required 0.3 ma until near the end of 0.4 sec hold-in time. In general this condition is not reached until after the next ping. On the other hand, if the first echo is received in the starboard channel, relay 4 is initially operated to the starboard position, but as soon as the port echo comes in, relay 4 is reversed because the differential current in the two windings does exceed 0.3 ma. Thus the control "prefers" the port side, and causes the torpedo to steer to starboard only if no port echoes are received.

#### 23.4 COMPARISON OF SYMMETRICAL STEERING AND PREFERRED-SIDE STEERING

A comparison was made on paper to determine the relative effectiveness of symmetrical steering and preferred-side steering. The width of the path within which the torpedo track had to lie in order to secure a hit was chosen as a measure of this effectiveness. This path width is a function of target dimensions, ratio of target speed to torpedo speed, direction patterns of the transducers, and track angle of the torpedo prior to the initiation of acoustic control. The meanings of these variables are illustrated in Figure 8. The German analysis assumed that the maximum acoustic-control range for echoes received from the ship was 200 m, and for wake echoes 50 m.

First, consider the qualitative behavior of the torpedo with the two types of steering. Suppose that the torpedo approaches the target on the port bow. If it is already on a collision course no echoes will be re-

ceived until the last few yards of the run, on account of the narrowness of the transducer patterns and the wide angle between them. The acoustic control does not affect the performance. If the torpedo tends to miss ahead of the target, ship echoes will be received in the starboard channel, and the torpedo will steer on a curved track in such a way that it tends to lead the target by a continually decreasing amount as it comes closer. This procedure will result in a hit. Moreover, since echoes are received only in one channel there is no difference between the symmetrical and preferred-side methods.

The difference becomes apparent when the torpedo tends to miss astern. In this case the first echoes are received in the port channel, so that the torpedo turns in that direction. Eventually, the torpedo heading is at 90 degrees to the ship's track, so that the port echoes from the ship and starboard echoes from the ship or wake arrive simultaneously. With symmetrical steering this condition is stable since, if the torpedo turns slightly to port, in the next ping interval the starboard echo comes in first and turns the torpedo back. When it has turned too far, the port echo arrives first and as a result the torpedo tends to run in to the ship or wake at right angles. Whether or not a hit is secured depends on the lateral distance from the ship's track at which this condition is set up, and upon the speed ratio. For very close misses astern, the torpedo will be close to the ship's track at the

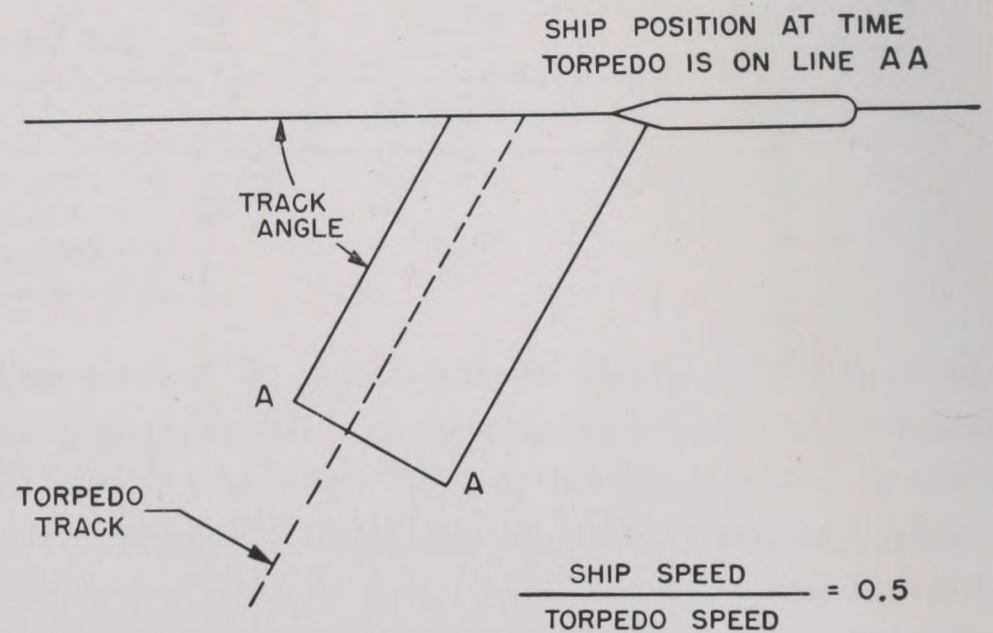


FIGURE 8. Diagram for steering analysis. AA = width of path within which torpedo track must lie in order to secure a hit (no acoustic control).

time it starts to run in on a perpendicular course, and a hit will be secured. For larger misses astern, the torpedo will merely cross the wake at right angles. Upon emergence, it will have lost acoustic contact, and will revert to gyro course, proceeding away from the target.

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With preferred-side steering with the preferred-side switch set to port, the torpedo would not run in on a perpendicular course after arriving at a point where the port and starboard echo-ranges are equal. Instead, it would continue to maneuver so that the port transducer beam alternately cut on and off either the bow of the target or the most forward part of the target from which echoes were received. Thus the torpedo would pursue the ship, and in general, hits would be secured from initial torpedo tracks corresponding to larger misses astern than is the case with the symmetrical method.

The improvement to be gained by using the preferred-side method is much more striking when the track angle is greater than 90 degrees. In this case the first echoes always come from the starboard side, so that with the symmetrical system the torpedo will cross the wake at right angles for all approaches except those lying in a very narrow path which would yield misses ahead in the case of nonacoustic control. With the preferred-side steering this is not the case, as was explained in the preceding paragraph.

By plotting out a number of torpedo tracks it is possible to ascertain the dependence of effective path width on track angle for the three cases of nonacoustic control, acoustic control with symmetrical steering, and acoustic control with preferred-side steering. This was done employing the following assumptions:

Torpedo speed	24 knots
Ship speed	12 knots
Torpedo turning radius	75 meters
Ship's length	100 meters
Ship's beam	15 meters
Maximum echo range (ship echoes)	200 meters
Maximum echo range (wake echoes)	50 meters

The results are shown in Figure 9A. The average path widths for the three cases in the two 90-degree sectors forward and aft of the beam are shown in Figure 9B. From this comparison the following conclusion may be drawn: Both the symmetrical and preferred-side methods provide a considerable increase in performance over the nonacoustic torpedo for shots in the bow sector. There is little difference in performance between the two methods. In the quarter sector, however, the symmetrical method is only slightly better than no acoustic control, but the preferred-side method gives a marked improvement. The preferred-side method has one fault which does not appear in the foregoing analysis: If the target detects the torpedo in sufficient time to take com-

plete avoiding action; i.e., to bring the ship head-on or stern-on to the torpedo, then the latter may be on the wrong side of the target when it comes under acoustic control. In this event the torpedo will attempt to steer on the tail of the wake, instead of on the ship. For this reason the estimated effectiveness of the preferred-side method should be reduced from the values indicated in the foregoing comparisons.

According to the statement of the Atlas Werke engineer who spent most time at the trials in Gdynia, the bulk of these experimental shots was made with symmetrical steering against targets moving at speeds of 10 to 15 knots. The observed performance was in good agreement with the theoretical analysis, at least in so far as the major items were concerned. Shots made on the quarter almost always resulted in misses astern because of the torpedo's attempt to cross the wake at right angles. Bow shots, however, were successful. A few of the Geier 1 units were equipped with a preferred-side control. Trials with

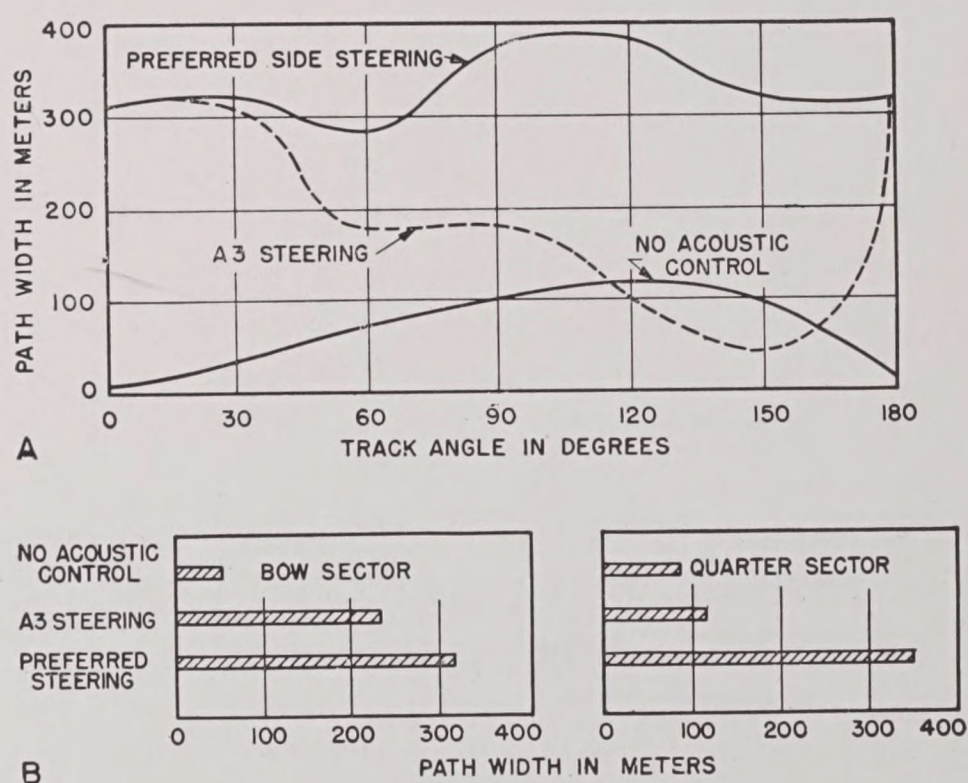


FIGURE 9A, B. Steering analysis curves.

these torpedoes tended to confirm the generalization that this type of steering was equally good for all track angles, provided the "preferred" side was properly chosen. Because of this superiority, the preferred-side control was incorporated in Geier 2.

## 23.5 STABILIZED TRANSDUCER ASSEMBLY

The self noise of the modified G7e torpedo in which Geier 1 was installed is said to be roughly equal to the reverberation level of the Geier signal corresponding to an echo range of 200 m. Hence it was



important to take all possible measures to minimize reverberation. It was found in the sea trials that excessive roll of the torpedo caused a marked increase in reverberation which seriously impaired the performance. This was to be expected on account of the wide angle between the two projector beams; a slight roll would throw most of the energy from one projector up into the surface. A similar difficulty, though not so great, resulted from pitching of the torpedo. In order to meet this problem, a stabilized transducer assembly, Pendel-Rose, was devised.

In this mechanism the four transducers are mounted on a framework suspended on athwartships bearings. A large piece of lead is attached to the bottom of the assembly making it pendulous. This feature tends to keep the transducers stable with respect to pitch. The pendulum bearings are secured to a plate behind the transducers. This plate is capable of axial rotation, and is driven by a small motor. On the back of the plate are mounted two

small mercury switches slightly inclined in opposite directions to the horizontal. When there is no roll, i.e., the transducer faces are vertical, both of these switches are open and the motor is stopped. When the roll exceeds 5 degrees, the mercury in one of the switches moves, closing a circuit which causes the motor to drive the plate around, reducing the roll to less than 5 degrees. The entire mechanism is very simple. It was stated that no electric interference in the signal channels was produced by the motor. The actual performance of the stabilized transducer assembly in reducing reverberation due to roll and pitch had not been extensively tested, but it was intended to use this feature in future Geier 2 units. Furthermore it was stated that such an assembly capable of withstanding short-period accelerations of 1,000 times gravity had been designed and tested for the aircraft torpedo.<sup>a</sup>

<sup>a</sup> See references 58-64 for additional material on topics in this chapter.



## Chapter 24

# BRITISH TRUMPER SYSTEM

### 24.1 INTRODUCTION

THE BRITISH Trumper torpedo is a prosubmarine anti surface-ship device, which was developed for use in the Mark 9 torpedo. The Mark 9 is a 21-in. torpedo that travels at a speed of 40 knots and has a turning radius of about 125 yd.

The block diagram of the Trumper control system is shown in Figure 1. The transducers used are quartz

course, the horizontal beamwidth of the transducers is used as the means of making initial acoustic contact with the target. The beamwidth of the transducers in the vertical plane is made very narrow in order to achieve a high directivity index. Diagrams of the quartz transducers for both the projectors and the receiving hydrophones are shown in Figure 2. The following are the characteristics of these transducers.

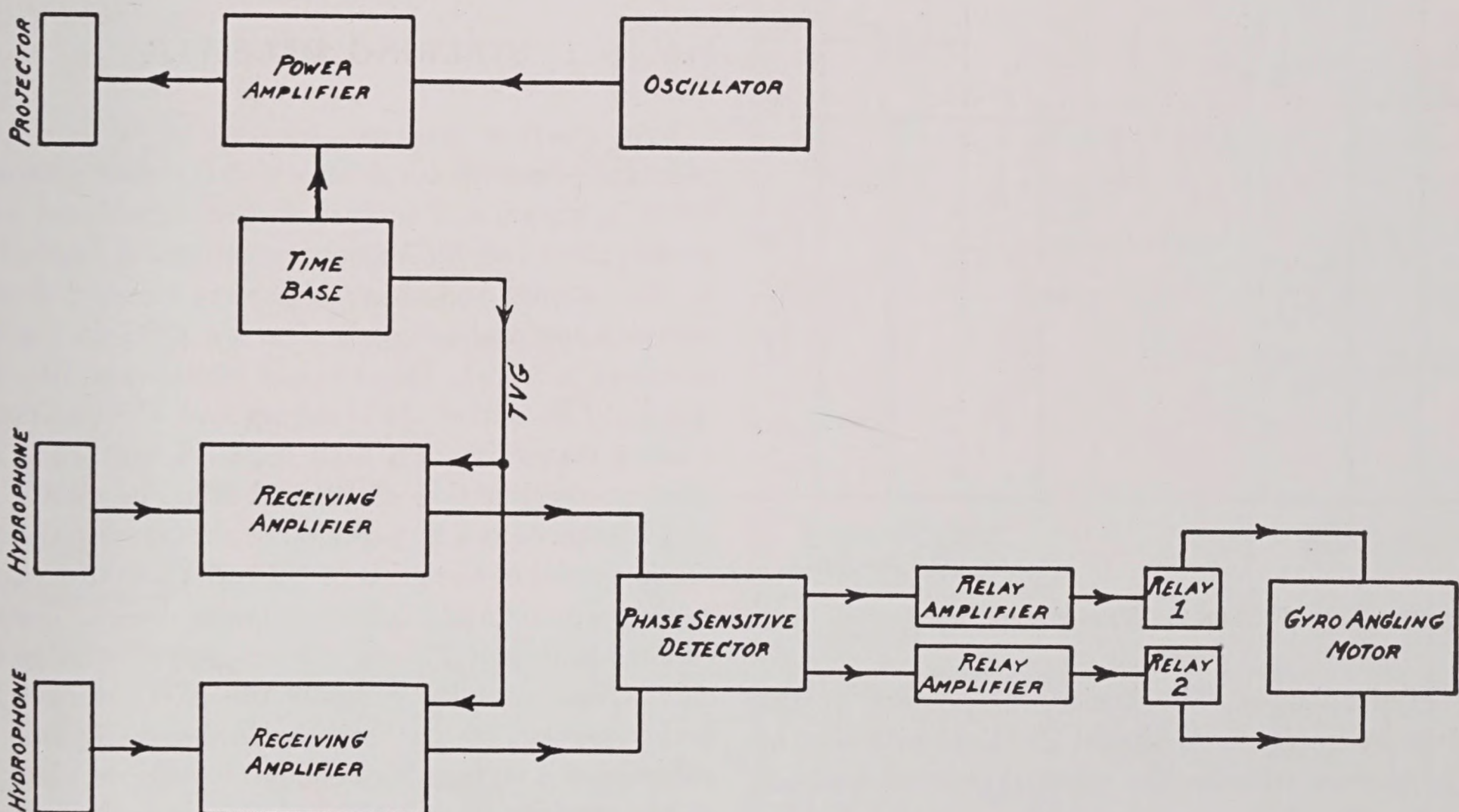


FIGURE 1. Block diagram of British Trumper.

sandwich type with separate transducers used for transmitting and receiving. The time base is a system of cams driven by the main motor shaft. These cams determine the 1-sec interval between transmitted pulses, the 3- to 5-msec length of transmitted pulses, the blanking, and application of TVG to the receiver channels.

### 24.2 TRANSDUCERS

The transducers are mounted in a flattened section on the nose of the torpedo. Since the torpedo is fired under gyro control to follow a straight gyro search

1. Projectors. The vertical pattern is 6 db down at 10 degrees off the axis and 10 db down at 16 degrees off the axis. The minor lobes are 13.5 to 14.5 db down and the first minor lobes are 23 degrees off the axis. The horizontal patterns for one-half the transducers are 5 db down at 45 degrees off the axis and 14 db down at 70 degrees off the axis; the minor lobes are negligible. When the projectors are connected with halves aiding, the 6-db down points are 25 degrees off the axis, the 10-db down points are 31 degrees off the axis, and the first minor lobes are 63 degrees off the axis and are 20 db down. When they are connected with halves bucking, the pattern is



bi-lobed with a zero on the torpedo axis. The angle between the maxima of the lobes is 60 degrees, the pattern is 12 db down at  $\pm 70$  degrees off the torpedo axis and 10 db down at  $\pm 5$  degrees off the torpedo axis.

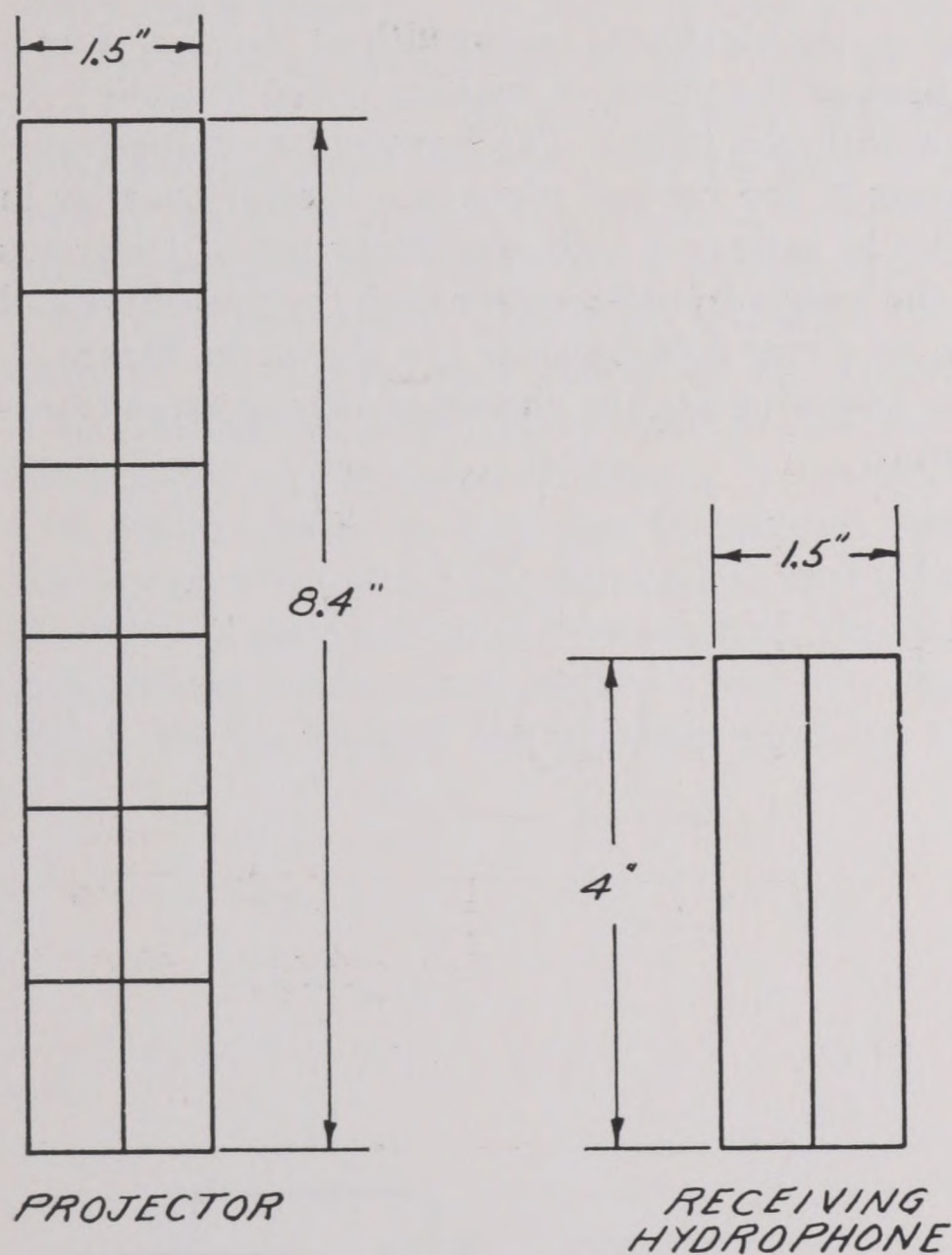


FIGURE 2. Transducers.

2. Hydrophones. The horizontal pattern of the receiver hydrophones is almost identical with that of the projectors, whereas the vertical pattern is about twice as wide.

#### 24.3

### TRANSMITTER

The diagram of the transmitter circuit is indicated in Figure 3. The oscillator V1 which operates from a plate supply of 300 v is not keyed by the time base but operates continuously. The driver stage V2 is driven by means of the oscillator and its plate circuit is keyed by means of a switch in the time base. The driver stage is coupled to the power amplifier by means of the transformer T1, the two secondary windings of which are so arranged that the grids of the power amplifier stages V3 and V4 are driven 180 degrees out of phase. The power amplifier is con-

nected to the two projectors by means of the transformer T2. The power-amplifier stage is keyed by means of a switch SW2 operated by the time base. This switch breaks the circuit between the cathodes of V3 and V4 and ground. The electric output of the power amplifier is about 300 watts and the efficiency of the projectors is such that about 200 watts of acoustic power is radiated into the water. The power supply for the power amplifier is mounted in a cylinder about 10 to 12 in. long and 3 in. in diameter and consists of a high-voltage 1,500-c generator which is driven by means of an air turbine. The output of the generator is rectified and supplied directly to the power-amplifier plates.

#### 24.4

### STEERING RECEIVER

The steering receiver consists of a four-stage resistance-coupled amplifier which is shown schematically in Figure 4. The first stage is considered as a preamplifier and no sensitivity control is applied to it. The second and third stages are blanked during transmission and are controlled by TVG during the listening interval. The circuits containing R9, P2, C7, and C8 control the blanking and TVG voltages. During transmission a high negative voltage is applied at the junction of R8 and R9. The circuit C7 and R9 serves as a fast-discharge circuit which allows the potential of the grids of V2 and V3 to drop quite rapidly immediately following transmission. The circuit consisting of P2 and C8 is a slow-discharge circuit which actually controls the TVG during the major portion of the listening interval. By this arrangement a voltage high enough to achieve blanking of the receiver during transmission is applied at the junction of R8 and R9, but very soon after transmission this voltage drops to the proper level for control of the receiver sensitivity during the listening interval and the rate of change of the sensitivity is then controlled by the circuit P2 and C8. The potential of the grid of V3 is maintained by way of R15 and the potential of the junction of R9 and P2. The entire receiving system contains two identical receivers like that shown in Figure 4 with the TVG circuits of these two receivers connected together as indicated in Figure 4. The inputs of these two receivers are obtained from two separate identical receiving hydrophones.

The fourth stage of the receiver is biased beyond cutoff by means of a negative voltage applied to its

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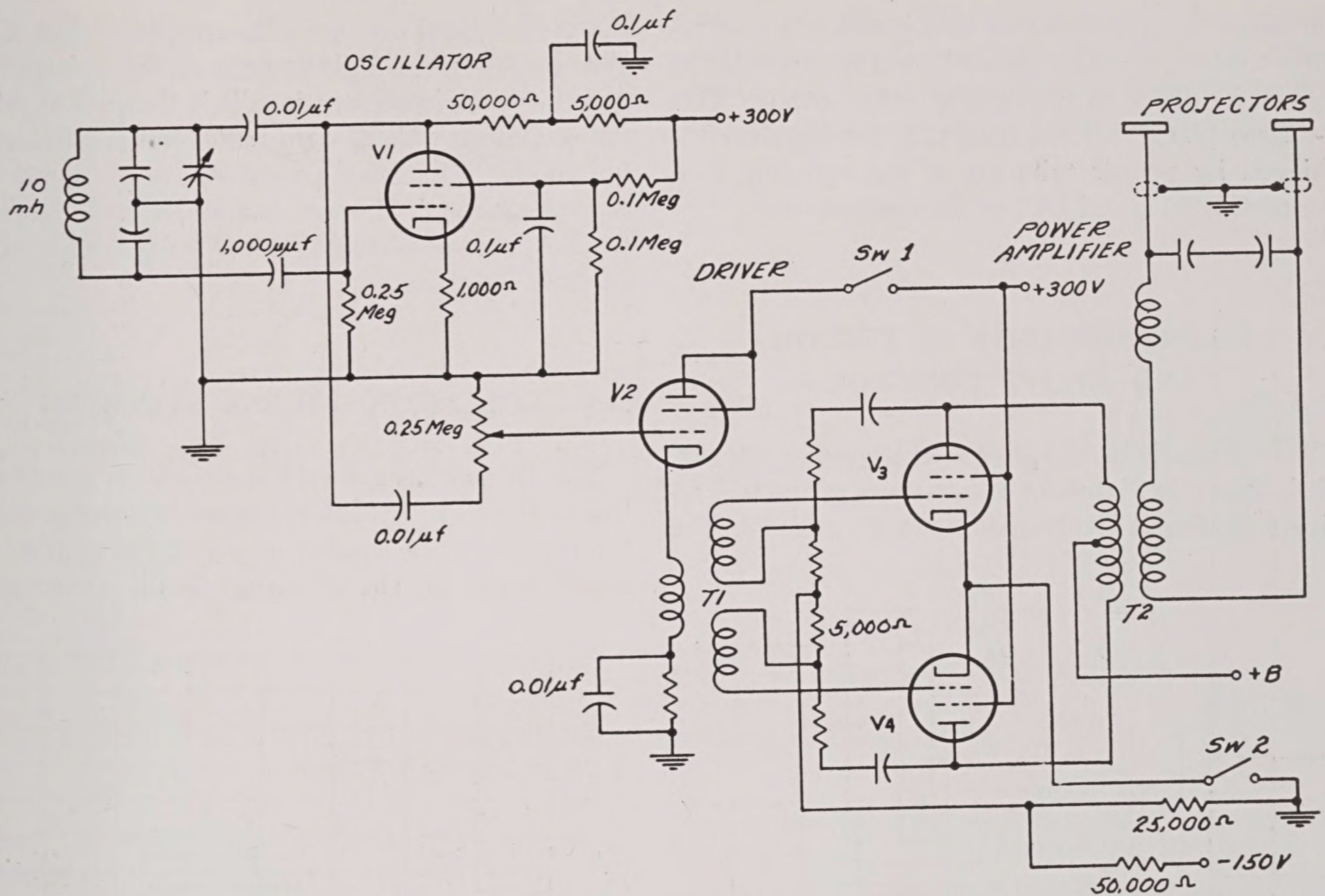


FIGURE 3. Transmitter.

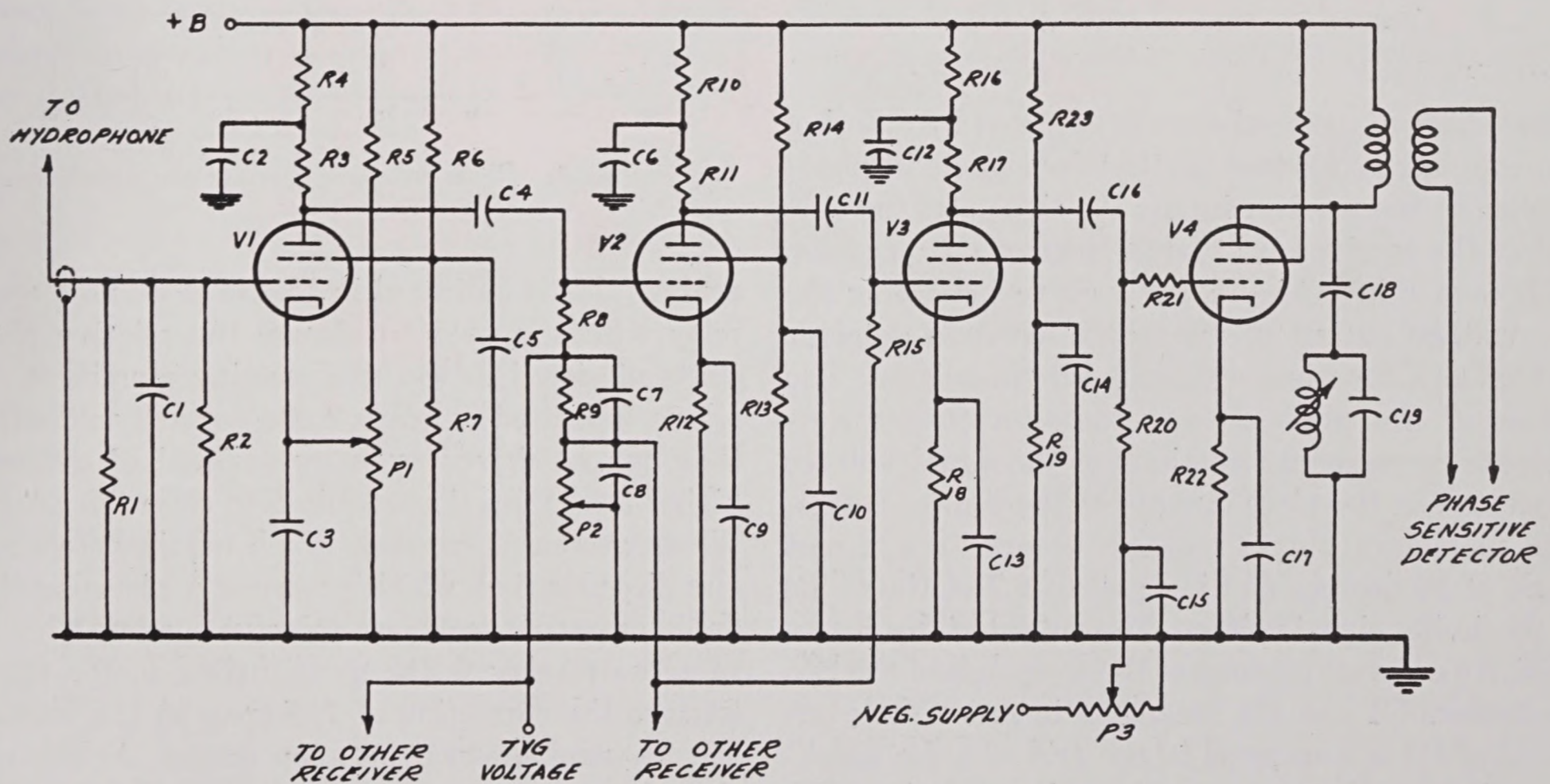


FIGURE 4. Schematic of steering receiver.

grid by way of P3, R20, and R21. When a signal is received on the hydrophone, this negative bias on V4 serves as an amplitude gate for the system, requiring that a signal level out of V3 be higher than a pre-

terminated value in order that any signal be generated in the plate circuit of V4. This stage also serves as a limiter stage since a level of about 3 db above the threshold signal level is required to produce limiting.

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The phase-sensitive detector circuit which is used requires that the applied signals be out of phase by 90 degrees in order to produce a zero output. This 90-degree phase difference in the two receivers is achieved by proper tailoring of the coupling condensers C4, C11, and C16 in the two receivers.

#### 24.5 PHASE-SENSITIVE DETECTOR AND RELAY CONTROL

The schematic of the phase-sensitive detector circuit is shown in Figure 5. The outputs of the two receivers appear at the transformers T1 and T2. The

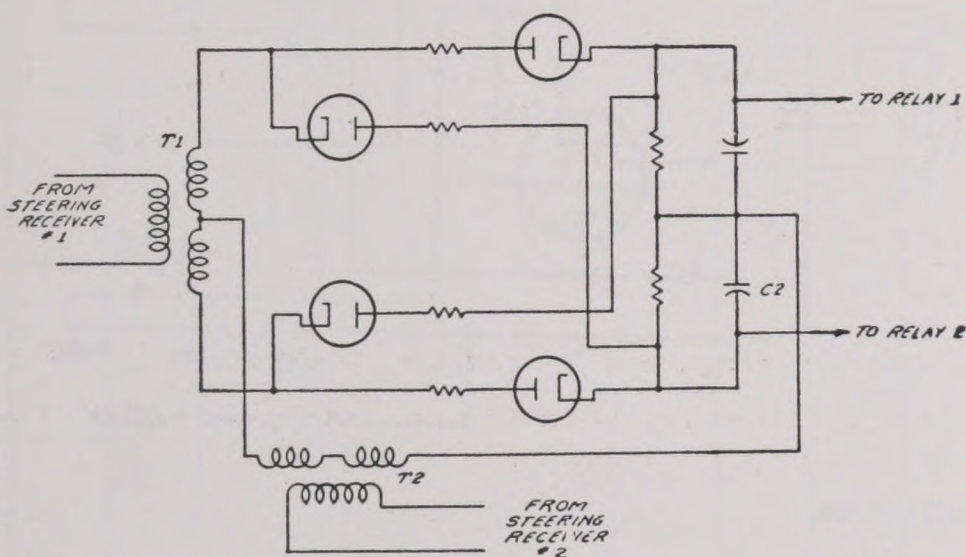


FIGURE 5. Phase-sensitive detector.

phase shifts in the receivers are adjusted by tailoring the coupling condensers so that for signals in phase applied at the receiver inputs the signals at the output of the receivers will be 90 degrees out of phase with each other. Figure 6 is a curve indicating the d-c voltage output of the phase-sensitive detector plotted as a function of target angle in degrees. The values of the phase-sensitive detector output voltages are expressed as fractions of the signal voltage generated in the plate circuits of the limiter stages. The maximum output voltage occurs at a target angle of 30 degrees and is equal to 0.7 of the value of the limiter signal voltage. The output of the phase-sensitive detector appears at the terminals of the two condensers C1 and C2 connected in series. The terminal of C1 is connected to the grid of a d-c amplifier which operates one steering relay and the other terminal of C2 is connected to another d-c amplifier which operates another steering relay. These steering relays are used to rotate the gyro by means of a gyro-angling motor. When a steering signal is received, one or the other of the relays is closed and this causes

the gyro-angling motor to change the setting of the gyro by 7 degrees. This amount of correction of the gyro per ping is chosen since it is the rate at which the torpedo is able to turn under the application of full rudder. The relay amplifiers are so biased that the voltage required to actuate the relays corresponds to the phase-sensitive detector output at a target angle of 3 degrees.

#### 24.6 COLLISION-COURSE STEERING

The British have done some work on a modification of the steering control system in order to permit the torpedo to be steered on a collision course. The modification of the steering circuit required to

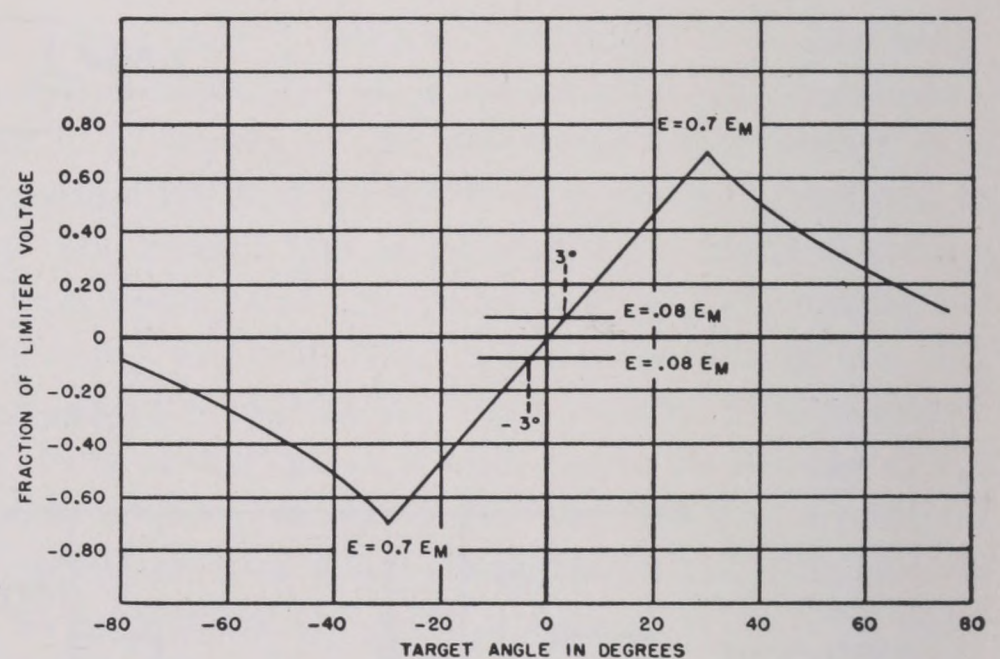


FIGURE 6. Phase-sensitive detector characteristics.

achieve this is indicated in Figure 7. *S* is a stepping relay which is used to change the relative phase-shifts of signal in the two steering amplifiers. The relays, indicated as relays 2, are normally closed, but they can be driven open by a signal of somewhat higher level than that required to close the relays 1. When a signal is received which requires steering in one direction but which produces a phase-sensitive detector output sufficient to actuate relay 1 but not to actuate relay 2, the gyro-angling motor will introduce the correction of 7 degrees in the course in the 1-second interval between echoes. At the same time the stepping relay *S* will be turned to introduce phase shift in the opposite sense between the two amplifiers amounting to 4 degrees which is the difference between the angle of correction introduced by the gyro-angling motor and the minimum sensitivity of the relay amplifiers. By this means the torpedo will

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asymptotically approach a course in such a way that the bearing of the target relative to the torpedo will remain constant. This is by definition the collision course. If the target angle at the time of initial con-

$S$  from operating. This condition will be continued until the torpedo is near enough to a pursuit course so that relay 2 will be unactuated when the torpedo will begin to correct to the collision course. It is not

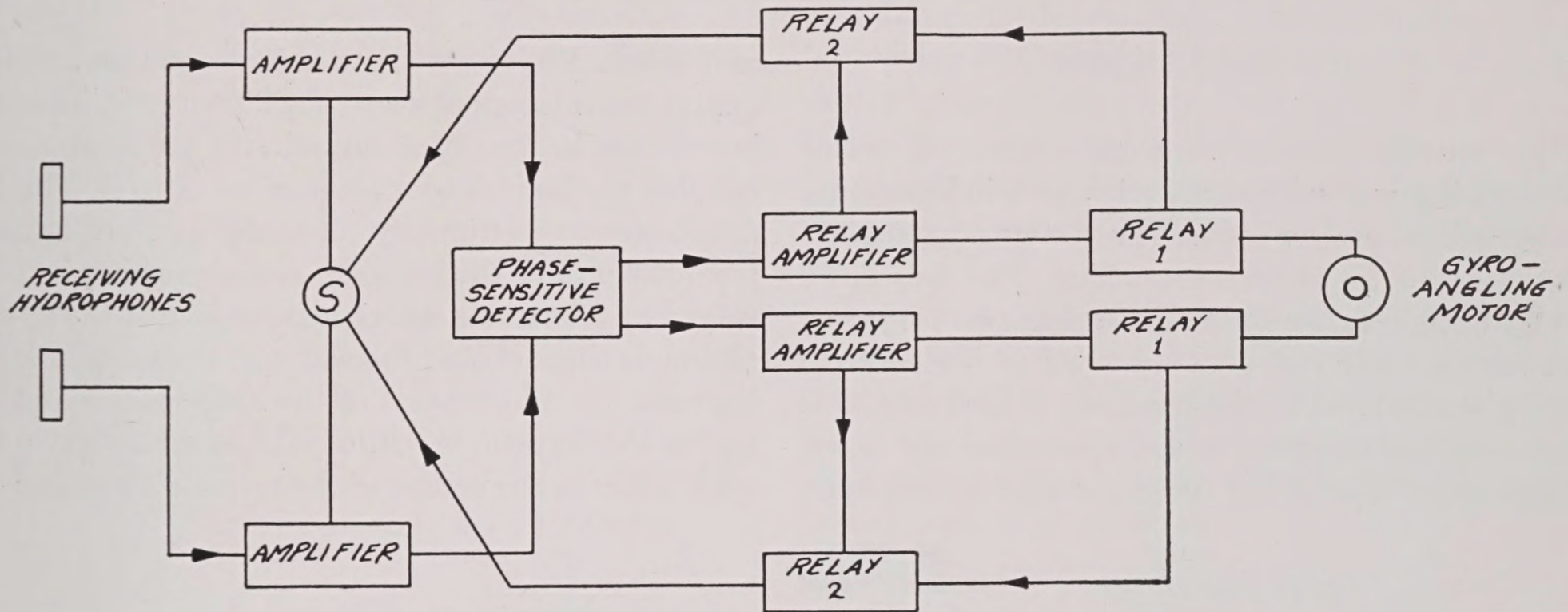


FIGURE 7. Block diagram of collision-course system steering.

tact is very large, the time which would be required to correct to the collision course would be excessive, so the relays 2 are provided to make the torpedo initially correct to a pursuit course under conditions of very large target angle where the signal applied to the relay amplifier is sufficiently large to actuate relay 2. Opening relay 2 prevents the stepping relay

known whether any torpedoes were ever operated with the collision-course system. The initial plan was to proceed with the simple steering system and to incorporate the collision-course system when it was sufficiently perfected.<sup>a</sup>

<sup>a</sup> See references 65 and 66 for additional material on topics in this chapter.



## Chapter 25

### BRITISH BOWLER SYSTEM

#### 25.1

#### INTRODUCTION

THE BRITISH Bowler torpedo utilizes an echo-ranging control system with two independent projectors and hydrophones. The system components were designed for aircraft launching. The projectors and hydrophones are so mounted that one projector transmits a beam out perpendicular to the torpedo axis on one side and a hydrophone placed beside it receives echoes from any target approximately to the torpedo axis. The other projector and hydrophone

of 0.16 sec. The projectors and hydrophones are both quartz transducers of about 3-in. diameter. The projectors are internally mounted and are acoustically coupled to the hull by means of an oil cell. The hydrophones are externally mounted and are isolated from the hull of the torpedo. An interesting fact observed in connection with the mounting of the hydrophones is the fact that the width of the annular space between the diaphragms of the hydrophone and the hull of the torpedo is critical. This annular space fills with water in the course of the torpedo's run and the

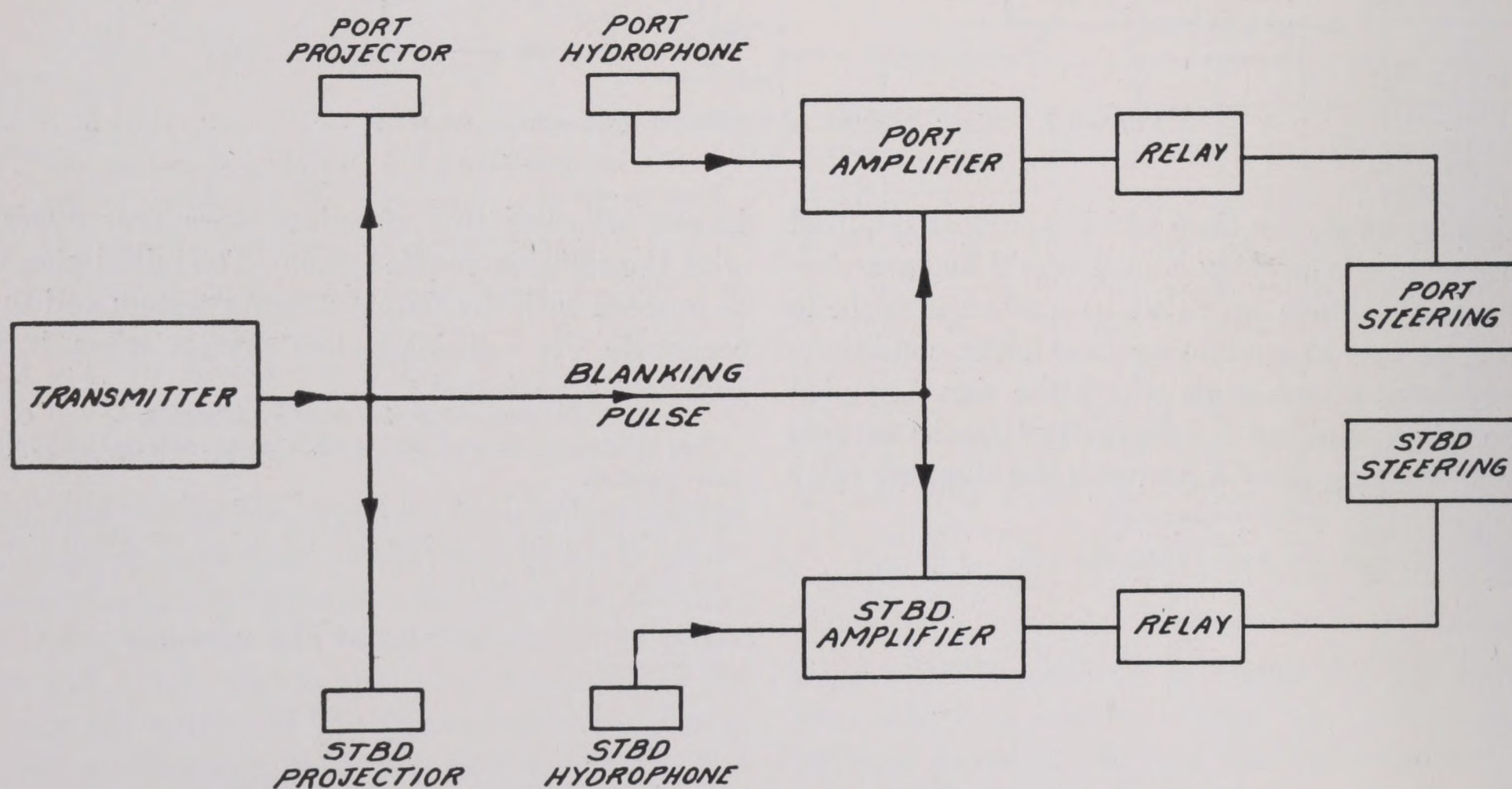


FIGURE 1. Block diagram of British Bowler system.

are located similarly on the opposite side of the torpedo. The torpedo is normally launched from a bow or stern aspect and if the torpedo misses the target, an echo will be received on one or the other of the receiving hydrophones, causing the torpedo to go into a hard turn toward the target. This arrangement requires that the range of the target be less than the diameter of the turning circle of the torpedo in order for it to make a hit.

A block diagram of the system is shown in Figure 1. The frequency of the transmitted signal is 26.7 kc; the length of the pulse is 2 msec with a ping interval

optimum value for the width of the space is 0.040 in. A greater width than this apparently introduces turbulence causing increased self noise, while a narrower width permits the water to form a shunt path across the isolation.

#### 25.2

#### ELECTRONIC GEAR

The transmitter consists of a blocking oscillator employing a 6N7 tube. The length of the pulses and the interval between pulses are controlled by the characteristics of this blocking oscillator. The oscilla-



tor drives the power amplifier which in turn drives the projectors through a coupling transformer. The power output of each projector is 15 watts. Since the blocking oscillator is its own time base, it is necessary that this oscillator be used to control the blanking and the TVG of the receiver. These functions are achieved by means of the double-rectifier system in-

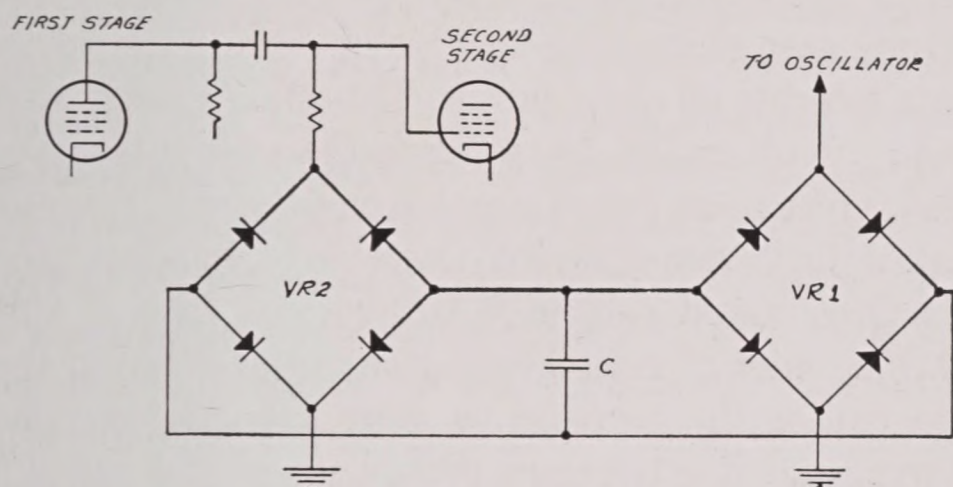


FIGURE 2. Details of blanking and TVG circuits.

icated in Figure 2. The virtue of this system is that it achieves blanking of the second stage of the receiver amplifier by a combination of increased bias on the grid and decreased value of resistance to ground from the grid without introducing transients into the system. The storage of charge on the condenser *C* by the rectifier VR1 is used for the TVG control. The receivers consist of two stages of resistance-coupled amplifiers followed by a single gas-discharge tube which is used to control the steering action. Considerable difficulty was encountered in obtaining control of the rudders by means of solenoids operated by relays from the gas tubes because space did not permit installation of adequate solenoids. The final solution of this problem was quite

unusual and was possible only because the torpedo is intended to have steering action applied just once during the course of an attack. The device consisted of two small cylinders each containing an explosive charge back of a piston. When an echo is received, indicating that the torpedo should turn in one direction, firing of the gas tube in the receiver causes the charge in the cylinder to be fired which in turn throws the rudder hard over in the proper direction. It is impossible for any further steering to take place until the torpedo is recovered and the cylinders are reset.

The size of the complete electronic chassis is approximately 5 x 6 x 12 in. The power supply consists of a 12-v Edison storage battery which is 12 x 4 x 3 in. The high-voltage plate supplies for the tubes are obtained by means of vibrators with transformers and rectifiers.

### 25.3

### PERFORMANCE

The dynamic sound pressure during transmission is between 2,000 and 6,000 dynes per sq cm at a range of 10 ft on the axis of a projector. Echoes of 50 to 100 dynes per sq cm have been obtained at a range of 100 yd off the beam of a stationary tanker. Echoes off the bow of such a ship at 100 yd range are approximately 20 to 30 dynes per sq cm. The peak noise level of the torpedo operating at a speed of 40 knots is from 5 to 8 dynes per sq cm. The signal-to-noise ratio under the most unfavorable conditions at 100 yards range is about 12 db. The average value is more nearly 20 db.<sup>a</sup>

<sup>a</sup> See references 66-68 for additional material on topics in this chapter.



## Chapter 26

### EVALUATION

ALL OF the echo-ranging control systems which have been described in the preceding chapters are systems which were developed under the stress of war with the chief objective to get a working device in the shortest possible time. In all cases compromises had to be made in order to avoid discarding something already developed and taking the necessary time to go back and re-engineer parts of systems which were found unsatisfactory. This resulted in most of the devices being made more complicated than necessary and containing components which are forced to operate under marginal operating conditions. The problem of maintenance and adjustment of the systems is in all cases more complicated than should be necessary.

In the case of the antisubmarine devices developed in this country, a device was desired which could be incorporated in the existing torpedo body already being used as a noise-steering torpedo. Since the body used in this torpedo is not capable of withstanding pressures corresponding to depths greater than about 400 ft, there was little immediate advantage to be gained in designing the electronic gear with a view to operating over a greater range of depth. The system developed by General Electric and engineered for production by the Leeds and Northrup Company fulfilled the requirements for this device in a quite satisfactory manner. It is one of the simplest echo-ranging systems which has been developed. The chief weakness of the system is the fact that the rate of dive and climb has to be quite severely limited. The maximum climb angle permitted is about 1.5 degrees which provides relatively little maneuverability in the vertical plane if a submarine under attack takes evasive action in the vertical plane. This is not a serious limitation when the device is applied to a body which is restricted to the upper 400 ft of water and is aircraft-launched against the swirl left by a diving submarine. If, however, the device is applied in a torpedo capable of operating over the range of depth to which the most modern submarines can operate, namely, about 1,000 ft, it is quite possible that evasive tactics in the vertical plane on the part of the submarine would be successful in evading the torpedo.

The General Electric NO181 system utilizes transmitter pulse lengths of about 30 msec with an amplitude-gate characteristic which prevents the device from steering on short pulses. This makes the system quite invulnerable to grenade-type countermeasures. The cut-on cutoff steering employed in azimuth makes the device quite invulnerable to noise countermeasures towed astern or thrown out from a submarine under attack. The cut-on cutoff steering system causes the torpedo to steer around the noise source, and if echoes are picked up on the far side again, the torpedo will steer on the echoes from the target. The device is, however, vulnerable to a decoy in the form of a very strong noise source at the target. This form of decoy will cause the torpedo to steer around the target rather than attack it.

The behavior of this system on wakes is quite interesting. The cut-on cutoff steering system in the azimuth plane causes the torpedo to steer parallel to the wake along one side. If the device steers on the wake, it will follow the wake to the target if started in the proper direction. In antisubmarine application, this is an advantage, since the torpedo when aircraft-launched is normally launched as near as possible to the swirl left by the diving submarine. This wake-following feature might well be a disadvantage in an anti surface-ship device, since in this case the torpedo is normally launched to run toward the target. The acoustic contact with the wake is likely to be such that the torpedo will follow the wake away from the target.

The Harvard NO181 system is a considerably more complicated device than the General Electric device. It utilizes target doppler for enablement, and in addition, uses an amplitude gate with a 30-msec transmitted pulse. This system is somewhat less vulnerable to countermeasures than the General Electric system and, in addition, high rates of dive or climb can be used since the device will not steer on surface or bottom echoes. The doppler system also prevents the device from steering on wake echoes. In a body with the limited capabilities of the one into which this device was built, there is some question as to whether the advantages gained by the additional complication of the doppler-enabling system were



worth while. However, in the development of an echo-ranging antisubmarine torpedo for operation at depths as great as 1,000 ft where vertical evasive tactics on the part of the submarine can become important, the additional rate of dive and climb permitted by the doppler-enabling system probably will become an important feature. This system is also invulnerable to grenade-type countermeasures because of the action of the amplitude gate. There is some tendency for the device to steer toward a noise source, so if the target is made a source of noise, the noise would simply aid the device in steering on the target. The behavior of the device in the presence of a continuous-noise source towed by the target or thrown out from the target is similar to that of the General Electric system. The torpedo might steer toward the noise source but after passing through it, it would be free to search on the target again; the sharp beam pattern of the transducer minimizes the effect of the countermeasure after the torpedo has passed. It should be noticed, however, that the use of a doppler-enabling system makes possible a simple evasion tactic, since it makes steering on a stationary submarine impossible.

The British Dealer torpedo was also designed as an echo-ranging antisubmarine torpedo, but relatively little is known of the nature of the electronic gear used. The methods used in the actual steering of the torpedo avoid the use of rudders which have to be operated through watertight seals on the body. The result was that two propulsion motors and two propellers are used and a means of moving the battery backward and forward is provided in order to steer the torpedo in the vertical plane.

All these antisubmarine torpedoes were designed so that they could be aircraft-launched. This placed relatively severe requirements on the design of all components entering into them.

The echo-ranging anti surface-ship torpedo which is simplest in principle and has the most limited objective is the British Bowler. This device is intended to have an acoustic operating range less than the turning diameter of the torpedo and it is intended that when the device receives an echo from one side, the rudders will be turned hard over and the torpedo will simply turn into the target. The transducers for the two separate transmitting and receiving systems are mounted on the two sides of the torpedo with their acoustic axes almost perpendicular to the axis of the body. The purpose of a device such as this is to increase the effectiveness of torpedoes launched off

the bow or stern of the target ship, but for large misses the acoustic control system does not add anything to the effectiveness of the torpedo.

One of the simplest of the anti surface-ship torpedo echo-ranging systems is the Geier 1 developed by the German Luftwaffe. The objectives of this device are somewhat limited since its operating range is only about 200 meters. This device also uses two independent sets of transducers, and acoustic control is inaugurated when an echo is received on one of the receiving hydrophones. However, the device differs from the Bowler device in that acoustic control is maintained until the torpedo strikes the target. This device is quite vulnerable to countermeasures, since it operates on any sudden change in signal level. It will not steer, however, on a continuous-noise countermeasure, because of the action of the special AVC circuit. It is also susceptible to steering on target wakes. There is an important difference between the behavior of this system and the General Electric system with respect to the target wake. The cut-on cutoff steering of the General Electric device causes it to steer parallel to the wake while the behavior of the German Geier system is such that when it steers on echoes from the wake, it tends to steer perpendicular to it. In any case, when the torpedo gets in such a position that it is closer to the wake than it is to the target, it will steer perpendicular to the wake. The Germans were doing considerable work toward improvement of the performance of this device in order to eliminate its vulnerability to the wake. The Geier 1 system was not intended to be used as a Service system but was simply intended to be used as a sort of guinea pig in the development of an improved device.

The Bell Telephone Laboratories [BTL] 157C system and the British Trumper systems are quite similar in their plan of operation. Both of these devices use a split-hydrophone system and the electronic gear in the receiver compares the phase of the signals on the two halves of the receiving hydrophones. In both cases the hydrophones and projectors are crystal. The British system uses quartz crystals and the BTL system uses ammonium dihydrogen phosphate crystals. The BTL device uses the same transducer for both projector and receiver. In the BTL device the target angle is actually measured by comparison of phase of signal on the two halves of the transducer and the measured value of the target angle plus a small correction angle is injected to the gyro cam plate by means of a mechanical device

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called a translator. In the British system an increment of angle is injected to the gyro cam plate whenever the acoustic signal indicates that the target is off the axis. On the basis of an analysis made by the BTL group, the system used by the British should be just as effective and it is capable of being made considerably simpler. One of the important criticisms of the BTL device is that in many ways it is excessively complicated. For example, the time base of the system consists of three double triodes and two relays, where the same operations can be performed by a simple set of cam-operated switches. The system whereby the target angle is measured also requires that a condenser and considerable circuit network have to be isolated from ground by a resistance of the order of 100 megohms. This is a requirement which probably cannot be maintained under all expected conditions of operation.

The German Geier system, the British Trumper, and the BTL system all suffer from the same difficulty with target wakes. The solution of the difficulty by the Germans and the BTL group is quite similar and involves use of a preferred-side steering. This is accomplished by setting a switch, operable from the outside of the torpedo, which causes the system to steer in the preferred direction when echoes are received in a listening interval which give steering information in both directions. With this arrangement the submarine skipper determines, before firing the torpedo, on which side of the target the torpedo will approach, and the preferred-side steering system is so set up that for that side of approach to the target the torpedo will prefer echoes from the target. In these systems it is assumed that the target will pursue the course estimated at the time of firing. If the torpedo is fired from a long running range and the ship is executing evasive maneuvers, there is a possibility that the ship will be in such a position that the torpedo will not be on the preferred side. In this case, the torpedo will prefer echoes from the wake and will be actually less likely to contact the target than it would have been without the preferred-side steering. The British also encountered another difficulty with their system in the presence of wakes. The broad transducer pattern in the azimuth plane causes the phase-sensitive detector to receive a long signal of continuously-varying phase which interferes with its action to such an extent that they were considering a change from a phase-comparison system to an amplitude-comparison system.

The Ordnance Research Laboratory [ORL] proj-

ect 4 device is an outgrowth of the Harvard NO181 system with the emphasis on antisurface-ship application rather than antisubmarine application. Since the problem of target wakes is a much more important problem in anti surface-ship applications, the doppler-enabling system gives this device considerable advantage, since it quite effectively eliminates the wake-steering problem. The preliminary results which have been obtained using the special transducer, which was developed with this system, indicate that the effective self noise of the torpedo in a system using this transducer is considerably less than the effective noise level with other types of transducer. The use of this transducer which has a very sharp beam pattern requires the snaky gyro-course for search in order to make acoustic contact with a target at an appreciable angle with the original gyro course of the torpedo.

Relatively little attention has been paid the countermeasure problem in the echo-ranging systems which were developed during the war. The fact that countermeasures for echo-ranging systems are, in general, different from those effective against a noise-steering device was depended on to make former devices effective. In future development, the fact that countermeasures, designed to operate against echo-ranging torpedoes, will be used, will have to be considered in the design of the systems themselves. The experience with the Harvard NO181 and the General Electric NO181 devices indicate that the use of relatively long transmitted pulses makes a system less vulnerable to countermeasures. In addition, methods of processing the received echoes will need to be devised in such a way that the criterion for steering can be varied from one unit to another so that when one type of countermeasure becomes effective, the system can be changed to make this countermeasure ineffective.

Since the self-noise level of the torpedo as measured on the receiving hydrophone determines the lowest level of received echo which can be effective in steering, the design of the transducer to minimize self noise is important. So far, the experience with the transducer which is used in the Harvard NO181, the General Electric NO181, and the ORL project 4 systems indicates that this transducer, which has a very sharp beam pattern and is mounted in the center of the nose, measures a lower level of self noise from the torpedo than is measured by broader beam-pattern transducers and transducers which are mounted at points in the nose not at the center. It is



not yet known whether this difference is due to the more effective front-to-back discrimination of the transducer used or to the fact that the small transducer mounted at the center of the nose is less affected by water-flow noise. Future investigations on the factors determining torpedo self noise should clarify this matter and make possible the more intelligent design of transducer systems.

In the antisurface-ship applications, some acoustic torpedoes provide for only azimuth control and the running depth of the torpedo is so set that it can make mechanical contact with the target or, if an influence exploder is used, the torpedo will pass close enough under the target to actuate the influence exploder. Experience so far indicates that self noise due to cavitation is decreased as the running depth of the torpedo is increased. Experience with the Mark 21 and Mark 31 noise-steering torpedoes which use the Mark 13 and Mark 18 bodies indicates that self-noise level decreases with increased depth down to a depth of about 50 ft. The decrease in self noise is of sufficient magnitude so that it is worth while operating the torpedo at the 50-ft running depth for the initial portion of an attack and then to use a vertical-steering system to bring the torpedo up to a shallow enough depth to make the attack effective at the end. The experience so far with the Mark 28 noise-steering torpedo indicates that operation as deep as 80 ft is desirable in the initial portion of the attack. Unless it is possible to design propellers which are entirely free from cavitation, it will probably continue to be profitable to operate torpedoes at these greater depths during the initial portion of the attack.

All torpedo echo-ranging systems so far developed have relatively complicated electronic gear which is so designed that the adjustments of the components of the system are critical, requiring quite highly skilled maintenance personnel at any station where the devices are made ready for operation. This condition need not always be true. With proper engineering the devices should be so worked out that, after adjustment is made in the factory, no further adjustment of any electronic components would need to be made in the field. It would be desirable to design the electronic panels so that they contain two or three replaceable units with all components well protected against mechanical injury and then supply test equipment for the field which will determine whether these unit components are operating properly or not. If a component is found not to be oper-

ating properly, it should be removed, replaced by another, and the defective component either discarded or returned to the factory for adjustment. This would greatly simplify the Navy personnel problem.

One of the most important needs in the development of any type of acoustic torpedo is the development of a torpedo body with a control system to which the information from the electronic panel can be easily applied. It would seem that an all-electric control system is preferable to the air control systems in current use on most torpedoes. In the case of the BTL device, a proportional control in azimuth is achieved by means of an extremely complicated mechanism to transfer the acoustic-steering information to the torpedo gyro cover plate. Use of an all-electric control system would make possible a very much simplified means of transferring this information to the gyro. In the case of the U.S. Navy Mark 20 torpedo, which was never used in the Service, the control system for both depth and azimuth utilizes selsyns to transfer the information from the gyro to the torpedo azimuth-control system and from the pendulum and bellows to the depth-control system. With this type of control it is possible, by the introduction of another selsyn in the depth system and also another selsyn in the azimuth system, to inject the correction information from the steering amplifier to the normal torpedo control. One of the difficulties in the Mark 20 is the fact that steering motors are used, and trouble has been experienced with the stability of this torpedo because of the sluggish action of the steering motors.

In order to achieve maximum range for an echo-ranging torpedo, it is necessary to have the ping interval great enough so that the transmitted signal can get to the target at the maximum range and back before the next transmitted signal. As the maximum range of the echo-ranging torpedoes increases, the information will become more intermittent and the difficulties in the use of an on-off steering system will become greater. This means that either a proportional azimuth-steering system as is used by BTL or an incremental azimuth system as is used in the British torpedoes will need to be used.

One of the chief advantages of an echo-ranging system is the fact that the range achieved is quite independent of the nature of the noise emitted by the target. In order to utilize this advantage to the maximum, large transmitter power outputs are essential. At the present time, the BTL NO181 system and the



ORL project 4 system use transmitters of 1.5-kw capacity which is probably not the largest power output feasible in an echo-ranging device. The utilization of power in a duty cycle needs some further study. In the above mentioned systems, the actual power output is determined by the plate voltage limitations of the tubes used in the power amplifiers. The power-supply problem actually resolves itself into the problem of transforming power from the propulsion motor of the torpedo into useful power on a duty-cycle basis for the transmitter without the

use of equipment which has an excessive weight or volume. In neither of the above systems is the power output of the transducer great enough to cause cavitation at its face during the transmitted pulse.

As the acoustic range of torpedoes is increased, the running range of the torpedo should be increased in a corresponding manner in order to utilize fully the advantages to be gained by acoustic control. This is another reason why attention should be given to the design of torpedoes for use with acoustic control systems.

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## GLOSSARY

- ACOUSTIC FREQUENCIES.** Sonic frequencies, range of audible frequencies, sometimes taken as from 0.02 to 15 kc.
- CAVITATION.** The formation of vapor or gas cavities in water, caused by sharp reduction in local pressure.
- CEILING SWITCH.** Pressure-actuated switch which keeps control system inoperative until torpedo exceeds some selected depth.
- CRYSTAL TRANSDUCER.** A transducer which utilizes piezoelectric crystals, usually Rochelle salt, ADP, quartz, or tourmaline.
- DIRECTIVITY INDEX.** A measure of the directional properties of a transducer. It is the ratio, in decibels, of the average intensity, or response, over the whole sphere surrounding the projector, or hydrophone, to the intensity, or response, on the acoustic axis.
- DOPPLER-ENABLING SYSTEM.** A circuit which allows only echoes having doppler to actuate the torpedo control system.
- ECHO REPEATER.** Artificial target, used in sonar calibration and training, which returns a synthetic echo by receiving, amplifying, and retransmitting an incident ping.
- FM SONAR.** Scanning-type sonar using a continuous frequency-modulated transmission signal.
- HYDROFOIL.** A body so formed that its motion through the water produces desired forces upon its surfaces.
- HYDROPHONE.** An underwater microphone.
- MAGNETOSTRICTION EFFECT.** Phenomenon exhibition by certain metals, particularly nickel and its alloys, which change in length when magnetized, or which, when magnetized and then mechanically distorted, undergo a corresponding change in magnetization (Villari effect).
- ODN.** Own doppler nullifier.
- PING.** Acoustic pulse signal projected by echo-ranging transducer.
- PIP.** Echo trace on indicator screen.
- PITCH.** Angular deviation from the line of course of a projectile taken in a vertical plane about its transverse axis.
- PROJECTOR.** An underwater acoustic transmitter.
- REVERBERATION.** Sound scattered diffusely back towards the source principally from the surface or bottom and from small scattering sources in the medium such as bubbles of air and suspended solid matter.
- SLC.** Simultaneous lobe comparison.
- SPECTRUM LEVEL.** Sound pressure level in a 1-c band.
- SUPERSONIC FREQUENCIES.** Range of frequencies higher than sonic, or "acoustic," frequencies. Sometimes referred to as ultrasonic to avoid confusion with growing use of supersonic to denote higher-than-sound velocities.
- TARGET STRENGTH.** Measure of reflecting power of target. Ratio, in decibels, of the target echo to the echo from a 6-ft diameter perfectly reflecting sphere at the same range and depth.
- THYRITE.** A material whose impedance varies inversely as the cube of the current passing through it.
- TRANSDUCER.** Any device for converting energy from one form to another (electrical, mechanical, or acoustical). In sonar, usually combines the functions of a hydrophone and a projector.
- TVG.** Time-varied gain.
- USRL.** Underwater Sound Reference Laboratories.
- VARISTOR.** A dry rectifier with the characteristics of a non-linear resistance whose value decreases with increasing applied voltage.
- X CUT.** A cut in which the electrode faces of a piezoelectric crystal are perpendicular to an X-, or electrical, axis.
- Y CUT.** A cut in which the electrode faces of a piezoelectric crystal are perpendicular to a Y-, or mechanical, axis.
- YAW.** Angular deviation from line of course of a projectile taken in a horizontal plane about its vertical axis.
- Z CUT.** A cut in which the electrode faces of a piezoelectric crystal are perpendicular to a Z-, or optical, axis.







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# CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS

<i>Contract Number</i>	<i>Name and Address of Contractor</i>	<i>Subject</i>
OEMsr-20	The Trustees of Columbia University in the City of New York New York, N. Y.	Studies and experimental investigations in connection with and for the development of equipment and methods pertaining to submarine warfare.
OEMsr-1131	The Trustees of Columbia University in the City of New York New York, N. Y.	Conduct studies and investigations in connection with the evaluation of the applicability of data, methods, devices, and systems pertaining to submarine and subsurface warfare.
OEMsr-287	President and Fellows of Harvard College Cambridge, Mass.	Studies and experimental investigations in connection with (1) the development of equipment and devices relating to subsurface warfare.
OEMsr-323	General Electric Company Schenectady, New York	Studies, experimental investigations, and development work in connection with submarine and subsurface warfare.
OEMsr-785	Western Electric Company, Inc. New York, N. Y.	Studies and experimental investigations in connection with Project 61.
OEMsr-1097	Western Electric Company, Inc. New York, N. Y.	Conduct studies and experimental investigations in connection with the development, design and construction of preproduction models of the acoustic and electronic arrangements required for Projects NO-149 and NO-157, and such other development, design, and construction work in this connection that may be required.
OEMsr-1294	Western Electric Company, Inc. New York, N. Y.	Conduct studies and experimental investigations in connection with production designs for the extension of Navy Project NO-94.
OEMsr-1051	Westinghouse Electric Corporation Sharon, Pa.	Studies and experimental investigations in connection with testing Mark 18 samples, and the design, development, construction, and testing of launching samples of an aerial torpedo, acoustically controlled and electrically propelled.
OEMsr-1053	Westinghouse Electric Corporation Sharon, Pa.	Studies and experimental investigations in connection with testing Mark 19 samples and the design, development, construction and testing of two hand-made samples of an acoustically controlled, electrically propelled submarine torpedo.
OEMsr-1370	Electrical Engineering and Mfg. Corp. Los Angeles, Calif.	Conduct studies and experimental investigations in connection with electric motor development.
OEMsr-1419	Leeds and Northrup Company Philadelphia, Pa.	Conduct engineering studies and design work on a controlled mine, including some model shop work; engineering design and construction of a small number of the preproduction models.



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### SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Executive Secretary, National Defense Research Committee [NDRC], from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

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*Service  
Project  
Number*

*Subject*

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NO-94	Mark — Mine
NO-149	Acoustic control for torpedoes
NO-157	Acoustically directed 21-inch torpedo for submarines
NO-181	Echo ranging control



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The subject indexes of all STR volumes are combined in a master index printed in a separate volume.

For access to the index volume consult the Army or Navy Agency listed on the reverse of the half-title page.

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